NOVA SCHOOL OF SCIENCE & TECHNOLOGY

DEPARTAMENT OF
INDUSTRIAL AND MECHANICAL ENGINEERING

WASTE TO 3D PRINTING: THE DEVELOPMENT OF ADDITIVE SYMBIOTIC NETWORKS

INÊS DE ABREU FERREIRA

Master in Engineering and Industrial Management

DOCTORATE IN INDUSTRIAL ENGINEERING

NOVA University Lisbon
October, 2022

DEPARTAMENT OF
MECHANICAL AND INDUSTRIAL
ENGINEERING

WASTE TO 3D PRINTING: THE DEVELOPMENT OF ADDITIVE SYMBIOTIC NETWORKS

INÊS DE ABREU FERREIRA

Master in Engineering and Industrial Management

Adviser: Helena Maria Lourenço Carvalho Remígio
Associate Professor, NOVA University Lisbon

Examination Committee:

Chair: Telmo Jorge Gomes dos Santos
Full Professor, NOVA School of Science & Technology

Rapporteurs: Graça Maria de Oliveira Miranda Silva
Assistant Professor with Habilitation, Lisbon School of Economics & Management, University of Lisbon

Luís Miguel Domingues Fernandes Ferreira
Assistant Professor, Faculty of Sciences and Technology, University of Coimbra

Adviser: Helena Maria Lourenço Carvalho Remígio
Associate Professor, NOVA School of Science & Technology

Members: Carina Maria Oliveira Pimentel
Assistant Professor, School of Engineering, University of Minho

António Carlos Bárbara Grilo
Full Professor, NOVA School of Science & Technology

Bruno Alexandre Rodrigues Simões Soares
Assistant Professor, NOVA School of Science & Technology

DOCTORATE IN INDUSTRIAL ENGINEERING

NOVA University Lisbon
October, 2022

Waste to 3D Printing: the development of additive symbiotic networks

To my family and friends,

"*Go as far as you can see; when you get there,*

you'll be able to see further."

(Thomas Carlyle)

ACKNOWLEDGMENTS

My sincere gratitude goes to Professor Helena Carvalho, who not only had the role of being my thesis supervisor but also always believed in me and motivated me, even in the most challenging times. A special thanks to Professor João Oliveira, who always had a good piece of advice to say to me and constantly pushed me to go further.

I also desire to express my gratitude to UNIDEMI researchers and members, in particular, Professor Radu Godina, for all the fruitful discussions and for guiding me in the first steps of my research and to António Grilo for providing me with all the necessary tools to develop this work and for keeping me motivated.

I want to thank the NOVA School of Science and Technology faculty and all its staff, especially to the Department of Mechanical and Industrial Engineering, for being supportive and helpful during this journey.

I also want to thanks to all the PhD colleagues I met from other Universities for all the productive discussions and for inspiring me.

A great thanks to all companies' experts involved in this work for giving their time and being available to talk to me, especially to Samantha Snabes and Guido Palazzo. A special thanks to Guido Palazzo, that received me in his country and always supported and motivated my research on this journey.

This research was supported by a PhD fellowship granted by Fundação para a Ciência e Tecnologia (SFRH/BD/145448/2019). Additionally, financial support was conceived through a research project funded by Fundação para a Ciência e Tecnologia (Project KM3D (PTDC/EME-SIS/32232/2017).

A huge thanks to all my friends who supported me during my journey and never made me give up, particularly to my special ones, Mariana Patrício, Ana Rodrigues, Rita Martins, Sónia Oliveira and Flávia Bastos.

Last but definitely not least, my gratitude goes to my family, especially my parents and my grandmother, for constant patience, love and support and for always encouraging me to go further and never forget my principles.

Abstract

Industry 4.0 technologies, such as additive manufacturing (AM) and blockchain technology, may drive the implementation of a new generation of circular economy strategies. However, the role of these new technologies in designing and implementing circular economy ecosystems is not a trivial issue. In this sense, this PhD research work intends to foster knowledge for developing industrial symbiosis networks within the AM industry - the so-called additive symbiotic networks. A systematic literature review reveals current circular economy relationships within the AM industry and highlights the potential of this industry to create and develop additive symbiotic networks in which plastic wastes from other industries may be used as material inputs for AM processes. However, given the digital nature of AM and considering challenges related to trust or implementing transactions, there is a need to find tools that enable additive symbiotic networks. Blockchain technology may be an enabler of such symbiotic networks, and its adoption within these settings may have implications for the supply chain of the additive symbiotic networks. Using an abductive research approach, two case studies are conducted concerning two additive symbiotic networks comprising companies that use AM processes to valorize plastic waste streams. Case study A proves there is space within the context of additive symbiotic networks to explore the adoption of blockchain technology and identifies a set of requirements that support the technology adoption in that specific network context. From this point, case study B is developed in order to understand the consequent implications of adopting such disruptive technology as blockchain in the supply chain structure of an additive symbiotic network. Results suggest that with the adoption of blockchain there is a reduction in the number of intermediary stakeholders involved in the network and an adaption of the value flows within the network. By offering a tool that helps to deal with the challenges associated with the additive symbiotic networks, exploring its adoption and some of its implications in the supply chain of those networks, this PhD thesis promotes the development of the additive symbiotic networks, contributing to the efficient use of natural resources, promoting the collaboration between industries and reducing waste streams to achieve more sustainable production.

Keywords: Additive symbiotic networks; Blockchain technology; Supply chain structure; Circular economy; Additive manufacturing; case study.

Resumo

As tecnologias que compõem a Indústria 4.0, como a manufatura aditiva (MA) e tecnologia blockchain, podem impulsionar a implementação de estratégias de economia circular. No entanto, o papel dessas novas tecnologias na conceção e implementação de ecossistemas de economia circular não é uma questão trivial. Este trabalho de doutoramento pretende fomentar o conhecimento para desenvolver redes de simbiose industrial na indústria da MA - as designadas redes simbióticas aditivas. A realização de uma revisão sistemática da literatura revela as relações entre a economia circular e a indústria da MA, destacando o seu potencial para desenvolver redes simbióticas aditivas. Nestas redes, resíduos ou subprodutos de outras indústrias podem ser utilizados como matéria-prima secundária em processos de MA. No entanto, considerando a natureza digital associada à MA e desafios relacionados com as redes de simbiose industrial, como a confiança ou a implementação de transações na rede, existe necessidade de encontrar ferramentas que possibilitem a implementação das redes simbióticas aditivas. A tecnologia blockchain pode ser uma facilitadora e sua adoção pode ter implicações para cadeia de abastecimento das redes simbióticas aditivas. Utilizando uma abordagem de investigação abdutiva, dois estudos de caso são desenvolvidos, em relação a duas redes simbióticas aditivas compostas por empresas que usam processos de MA para valorizar fluxos de resíduos e subprodutos. O estudo de caso A comprova que há potencial no contexto das redes simbióticas aditivas para a adoção da tecnologia blockchain e identifica um conjunto de requisitos que suportam a adoção desta tecnologia no contexto específico da rede em estudo. O caso de estudo B é desenvolvido com o objetivo de compreender as implicações da adoção da blockchain na estrutura da cadeia de abastecimento de uma rede simbiótica aditiva. Os resultados sugerem que com a adoção da blockchain há uma redução no número de entidades intermediários envolvidas na rede e há uma adaptação dos fluxos de valor dentro dessa mesma rede. Ao oferecer uma ferramenta que ajuda a lidar com os desafios associados às redes simbióticas aditivas, explorando a sua adoção e algumas das suas implicações na cadeia de abastecimento dessas redes, esta tese de doutoramento promove o desenvolvimento das redes simbióticas aditivas, contribuindo para uma eficiente utilização de recursos naturais, promovendo a colaboração entre as indústrias e reduzindo os fluxos de resíduos para alcançar uma produção mais sustentável.

Palavas chave: Redes simbióticas aditivas; Tecnologia blockchain; Estrutura da cadeia de abastecimento; Economia circular; Manufatura aditiva; caso de estudo.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

AM	Additive manufacturing
GBX	Gigabot X
ISN	Industrial symbiosis network
PC	Plastic Polycarbonate
PCR	Post-consumer recycled
PET	Polyethylene Terephthalate

1

INTRODUCTION

This first chapter is an introductory chapter to the dissertation. It includes the aim, motivations, objectives, and research questions. It also presents a general description of the research approach used and consists of an overview of the PhD thesis.

1.1 Aim

Recent trends and patterns are emerging through technological, economic, and social progress. As a result, new consumption habits are putting growing pressure on resource consumption and environmental protection. There is a need for innovative or modified processes to avoid or reduce environmental harm and promote business sustainability (Genovese et al., 2017). The circular economy allows to exploit the regeneration of material flows and to find a balanced growth between economic development and the sustainable use of the resources (Zhu et al., 2010). The 4R framework (reduce, reuse, recycle and recover) is one of the core principles of the circular economy that practitioners and academics have been using (Kirchherr et al., 2017). This framework considers the following principles: i) Reduce: includes discussions on rethinking, refusing, minimization, redesigning, reducing, preventing resource use and preserving natural capital; ii) Reuse: includes discussions on reusing (waste is excluded), cycling, repairing, closing the loop and refurbishing of resources; iii) Recycling: includes discussions about recycling, closing the loop, remanufacturing and reuse of wastes; iv) Recover: includes discussions about the incineration of materials with energy recovery. By reducing and removing waste and emissions from industrial processes, the circular economy aims to keep waste within the assimilative capacity of ecosystems (Kennedy & Linnenluecke, 2022). According to Chertow (2000), waste exchanges formalize trading opportunities that can be local, regional, national, or global through the creation of a hard-copy or online list of materials one organization would like to dispose of and another organization might need, and this form of exchange is typically one-way and focused at the end-of-life stage. These exchanges achieve different inputs and outputs savings on a trade-by-trade basis, rather than continuously, and they feature an exchange of materials rather than water or energy.

It is, however, necessary to have in mind some of the definitions of the Waste Framework Directive (WFD) (European Commission, 2020a), namely that a product is defined as "*all material that is deliberately created in a production process*", and a production residue is defined as "a *material that is not deliberately produced in a production process but may or may not be a waste*". WFD also defines waste as "*any substance or object which the holder discards or intends or is required to discard*". Still, WFD settled out four conditions that a production residue must have in order to be considered a by-product: i) further use of the substance or object must be specific; ii) the substance of object is produced as an integral part of a production process; iii) further use is lawful, i.e. the substance or object will not lead to overall adverse human health or environmental impacts and iv) the substance or object can be used directly without further processing other than regular industrial practice. It is also important to highlight that end-of-life criteria are specified for when certain wastes cease to be waste and obtain a status of product (or a secondary raw material) (European Commission, 2020b).

To implement a circular economic model, it is necessary to adopt strategies that contribute to expanding the concepts of eco-efficiency and industrial symbiosis (Álvarez & Ruiz-Puente, 2017). Therefore, efforts have been made by researchers and policymakers to find new approaches and conceptions that could decidedly contribute to managing waste more effectively and efficiently and promote materials recycling and reuse. Industrial symbiosis has its genesis in biology in which symbiosis represents the association of individuals belonging to different species in a mutual benefit relationship (Neves et al., 2020). This concept transposed to industries with the ultimate objective of producing more without spending more resources or energy through cooperation between industries.

Even though the exchange of energetic and material resources is the most frequent, equipment and services or information and knowledge resources are often included in an industrial symbiosis setting. These actions can be understood, as highlighted in Ferreira et al. (2019), as an exchange of resources in a value network created by several stakeholders. From Ponis's (2021) point of view, industrial symbiosis seeks to create inter-organizational networks designated by Industrial Symbiosis Networks (ISNs). These networks promote the symbiotic functioning of ecological systems in which traditionally independent sectors or industries exchange material, waste, energy and by-products with minimal waste produced. In this PhD research work, a focus on waste and by-product exchange is given.

Recently additive manufacturing (AM), a hyper-flexible technology, has become a source of product and process innovation, enabling customized and personalized products (for example, for aircraft parts, dental restorations, medical implants, automobiles, and even for fashion products (Matos et al., 2021). It provides a new set of opportunities for exploring and developing a new logic for creating and capturing value from such products and processes (Piller et al., 2015). This type of manufacturing is critical to the realization of a circular economy, as it is decentralized and distributed; it eliminates wasteful steps of traditional manufacturing; it extends the range of products that can be manufactured; and it saves materials, time, and logistics operations (Ford & Despeisse, 2016). In Hettiarachchi et al. (2022), the authors assessed how AM can enable circular economy and how supply chain actors, critical decisions, drivers, operational practices, and circular economy's implementation strategies interact to operationalize AM in the circular economy context. To boost the circular economy, Singh & Kumar (2022) presented a thorough and up-to-date discussion on breakthroughs in AM by identifying new products and strategies for product development; while Gouveia et al. (2022) argued that to establish the role of AM in the future circular economy, there is increasing demand for data regarding its environmental and economic performance.

In addition, adopting AM technologies may stimulate the rise of some trade-offs with the environmental and social performance of a company, such as:

- Energy use: at a process or machine level, most AM processes use more energy than traditional processes. However, AM allows us to produce complex parts in a single step. AM makes it easier to use renewable energies and enables distributed manufacturing (Rejeski et al., 2018).
- Waste: it is expected that AM uses less material and produces less waste. However, little information about the quantity and origin of the waste generated during AM processes is available (Rejeski et al., 2018).
- Safety and occupational hazards and health risks: even though the societal and economic vantages of AM are still hardly explored (Khorram Niaki et al., 2019), this technology has the potential to reduce hazards. However, the effect on workers' safety and health is still under discussion, namely in what is a concern to the utilization of powder (Matos & Jacinto, 2018).

- Social manufacturing: with AM, the role of customers changes from passive to active agents in the manufacturing of products. This change allows for the opportunity to produce customized products according to the needs of each customer (Naghshineh et al., 2021).
- Local manufacturing: the proximity between manufacturers, suppliers and customers is essential and localized production is desirable (Naghshineh et al., 2021).
- Education and training: considering the rapid acceleration and adaptation of AM technologies, there is a need for training and educating a knowledgeable workforce about how to employ AM technologies, processes and materials (Naghshineh et al., 2021).

Many authors suggest several different applications. For example, Rosa et al. (2020) analysed 30 studies regarding how AM can support a circular economy. Hettiarachchi et al. (2022) performed a systematic review comprising 51 journal articles to identify the conceptual elements of AM integration into the circular economy. An assessment and demonstration of a circular economy strategy for reducing CO_2 emissions through concrete recipe optimization is presented by Favier & Petit (2022). Arifin et al. (2022) examined the sustainable impacts of AM from an environmental, economic, and social perspective. Moreover, Naghshineh et al. (2021) identified in their review 42 different social impacts achieved by the AM and their association with relevant stakeholders. Lastly, Rodriguez Delgadillo et al. (2022) provided operational guidance to decision-makers for improving AM processes in terms of quality and sustainability. Several studies claim that to achieve sustainable manufacturing, recycling and AM must be combined (Di & Yang, 2022; Stefaniak et al., 2022a; Wu et al., 2022). Thus, there are significant challenges and opportunities in the industry related to recycling and AM (Wu et al., 2022).

Despite the potential within the AM industry, there is a lack of literature that supports the development of ISNs within the AM in the context of the circular economy (Ferreira et al., 2021). In this sense, the use of AM technologies in circular economy ecosystems is extended and designated as "additive circular ecosystems" in this PhD research work. These additive circular ecosystems are supported by ISNs that use AM technology to improve the circularity of materials. As a result, this PhD research work intends to contribute to the literature regarding these topics by providing a proposal of a new concept: the additive symbiotic networks.

The additive symbiotic networks involve inter-organizational relationships between stakeholders manifested through interactive activities. Hence, like in an ISN, the additive symbiotic networks involve different stakeholders exchanging resources, creating a value network with a power distribution among the stakeholders involved. Like in any other peer-to-peer context of services and marketplaces, trust plays a critical role in developing relationships and interactions (Hawlitschek et al., 2018; Ponis, 2021), especially when considering a symbiotic relationship between industries with no cooperative mechanism established between them until the time of the symbiotic exchanges (Ponis, 2021). Furthermore, considering the need to find tools that support the development of the symbiosis process, particularly for the exchanges between stakeholders (Yeo et al., 2019) and considering AM characteristics, such as its digital nature, it is expected that the additive symbiotic networks face similar challenges. Thus, there is a need to adopt new technologies that meet the requirements for developing additive symbiotic networks.

Industry 4.0 technologies may drive the implementation of a new generation of circular economy strategies driven by a digital economy. However, it is not clear what the requirements are to implement those technologies in a real case setting. For example, Patyal et al. (2022) theorize about the link between the adoption of Industry 4.0 technologies, such as blockchain and AM, and circular economy sustainable operations; still, those authors recognize the need to do substantial empirical work through a large-scale survey or a case study for validation of the proposed framework. Authors such as Tseng et al. (2018) stated that there is a need to address how Industry 4.0 technological innovations can be used for data-driven analyzes to generate liable information among industrial symbiosis partners and used to measure corporate culture and behaviour, including mutual trust to enhance industrial symbiosis processes. In this sense, blockchain technology has been recognized as a tool that can be adopted to promote ISNs (Gonçalves et al., 2022; Li & Pinto, 2021). This technology is expected to be adopted to enable the development of additive symbiotic networks. Currently, there is already work and research on adopting blockchain technology to enhance an ISN setting, as seen in Gonçalves et al. (2022) and Ponis (2021). According to Xu & Viriyasitavat (2019), adopting blockchain technology in a collaborative business process setting poses several interoperability challenges related to time, prejudice and trust in process execution and information. The application to real case scenarios, extending the existing studies related to financial trading to other applications domains and describing factors that contribute to the creation of smart contracts requires future research.

Ghimire et al. (2022) focused on the synergies between AM and blockchain technologies. The authors mentioned that despite the existing contributions in the literature for understanding how blockchain technology potentially affects supply chains, those studies are not tailored to the AM context. Moreover, both technologies (i.e., AM and blockchain) have still not been used in a scalable manner, posing challenges for companies aiming to adopt them. There is no real-life blueprint for developers or researchers to follow (Kurpjuweit et al., 2019). Hence, despite its potential to be adopted in an additive symbiotic setting, authors such as Peck (2017) and Sanka et al. (2021) referred that the adoption of blockchain technology should be carefully evaluated, as it depends on the diversification of interests within the companies involved and the problem that the technology is trying to improve. So, there is still a need for more research in a real-case scenario to find out how to frame the problem and identify requirements for the technology deployment.

Besides, exchanging resources between different companies creates an interdependency in an additive symbiotic network setting because organizations cannot control all the resources needed for their main activities (Herczeg, 2016). It is managed cooperatively, with different strategic alliances (Boons & Baas, 1997), creating a supply chain. The supply chain structure refers to the different "links" between any adjacent supply chain members. According to Guo et al. (2017), these links refer to the relationships and connections between the supply chain parties that have cooperation mechanisms, contributing to the establishment of the whole supply chain. Adopting innovative technologies such as blockchain promotes decentralized management of the supply chain and, thus, may impact the intrinsic supply chain of an additive symbiotic network. To Xue et al. (2020), the decentralized management of the supply chain is a breaking chain structure that enables all the stakeholders to establish an equal and open network model through information sharing. Despite the increase in successful examples of blockchain technology applications in supply chains (Oh et al., 2022), the literature regarding the changes that may occur in the supply chain structure of an additive symbiotic network with the adoption of this innovative and disruptive technology is still in its very beginnings.

Considering the lack of research on the topics under study, this PhD research work is investigating a new phenomenon that is not fully understood yet. Thus, as Figure 1-1 shows, this PhD research work intends to foster knowledge for developing additive symbiotic networks. Furthermore, this PhD research work explores tools such as blockchain technology that can be adopted in an additive symbiotic network setting, supporting the exchanges between the stakeholders involved in the network and enhancing the symbiosis process. Additionally, the implications of adopting such innovative technology as the blockchain in the supply chain of an additive symbiotic network are explored.

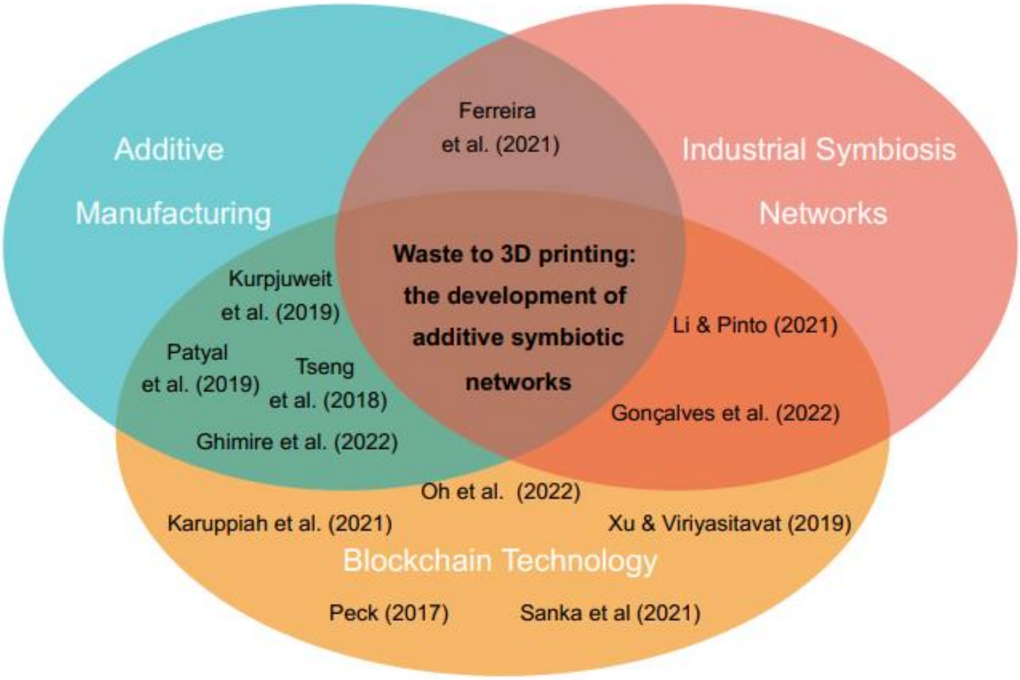


Figure 1-1 Main research gaps and positioning of this PhD research work

This PhD research work resulted in four different papers that were submitted to International Journals, namely:

- The paper entitled *Waste Valorization through Additive Manufacturing in an Industrial Symbiosis Setting* (Ferreira et al., 2021) published in Sustainability.
- The paper entitled *Boosting Additive Circular Economy Ecosystems using Blockchain: An Exploratory Case Study* (Ferreira et al., 2023), published in Computers & Industrial Engineering.
- The paper entitled *Implications of the Blockchain Technology Adoption in an Additive Symbiotic Network*, under revision in the International Journal of Cleaner Logistics and Supply Chain.
- The paper entitled *A Blockchain Architecture with Smart Contracts for an Additive Symbiotic Network – the B-PET's case study*, submitted to the Journal of Operations Management Research.

1.2 Objectives and research questions

To encourage the sustainable use of natural resources and promote the concepts of circularity and sustainability, and in line with the sustainable goals number 9 and 12, "*Industry, Innovation* *and Infrastructure*" and "*Responsible consumption and production*", respectively, from the seventeen main sustainable development goals proposed by the United Nations in the Agenda 2030, this PhD research work aims to encourage the development of additive symbiotic networks and explore tools that enable the effective implementation of those networks. Therefore, the following research questions (RQ) are addressed:

- RQ1 – How to promote ISNs in the AM context?
- RQ2 – What are the requirements to make use of blockchain technology in an additive symbiotic network?
- RQ3 – What are the implications of blockchain technology adoption in the supply chain structure of an additive symbiotic network?

Consequently, the objectives of this PhD research work are:

- Identify what resource exchange can occur and how wastes can be used as material inputs for AM processes.
- Identify a methodology for characterizing an additive symbiotic network and exploring the power distribution among its stakeholders.
- Identify the requirements to adopt blockchain technology in an additive symbiotic network.
- Characterize the implications in the supply chain structure of an additive symbiotic network in a scenario that considers the adoption of blockchain technology.

1.3 Research approach

To carry out this PhD research work, a research approach was followed comprising three main research phases, illustrated in Figure 1-2. As highlighted in sub-chapter 1.1, there is currently a lack of research when exploring the topics of additive symbiotic networks and the adoption of blockchain technology in such settings. Thus, this study adopts an exploratory character.

The literature review conducted on the topics under study included two different methodologies. One unstructured review that includes relevant references about ISNs and AM and other supporting topics, e.g., the additive symbiotic networks, the stakeholder theory, and the stakeholder value network. This approach follows a purposive sample of articles, i.e., the literature included in this thesis was based on central and pivotal articles published in the top journals in the field.

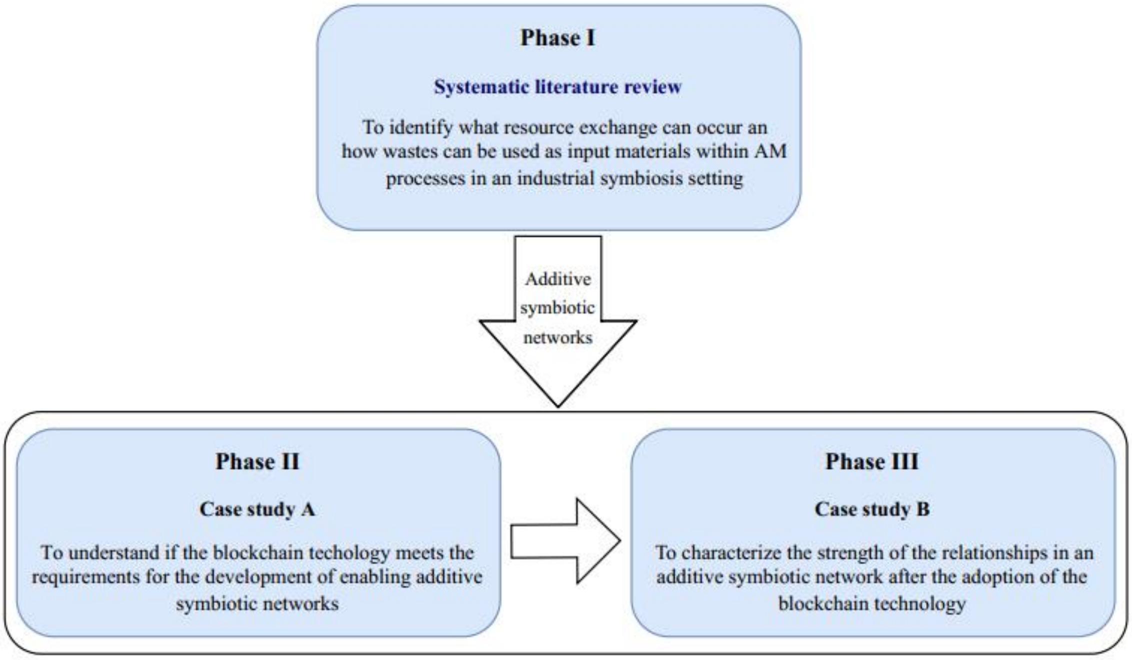


Figure 1-2 Research approach overview

The literature review also included a systematic literature review corresponding to this PhD thesis's first research phase (Figure 1-2). The systematic literature review was conducted on the topics of ISNs and the AM industry. Additionally, considering the exploratory character of this PhD research work, this was considered the most suitable methodology to assess this PhD's first research question (**RQ1** - *How to promote ISNs in the AM context?)*.

Two other research phases (phases II and III) were carried out from phase I. A methodology based on two case studies was selected to give insights and foster knowledge about a new phenomenon.

A variety of materials can be used in AM processes and technologies. Among these, polymer materials (including plastics) are considered one of the most used materials in the AM field (Ford & Despeisse, 2016; Jafferson & Chatterjee, 2021). The literature shows that AM has increasing potential for recovering value from a multiplicity of wastes and by-products into value-added products (Ferreira et al., 2021). Thus, in this PhD research work, the relevant criteria for understanding the phenomenon under study was to focus on AM technologies that employed plastic waste streams as materials inputs. Two case studies concerning two different ISNs that used AM technology to valorize plastic wastes were developed.

Furthermore, according to Voss et al. (2002), not all researchers use theoretical or literal sampling in case research. Sometimes convenience sample is used. For this PhD research work, this was the criteria used to choose the two different companies that formed the ISNs that used AM technology to valorize plastic waste.

Case study A comprises a company called re:3D, located in Texas, USA, that had participated in a project called "*From Trash To Treasure*", which allowed the company to use production wastes from other industries to produce 3D printed pieces of furniture and thus, motivating the development of an additive symbiotic network. Case study B includes B-PET, a company located in Buenos Aires, Argentina, that supplies AM technology, equipment and services, allowing other organizations to incorporate plastic waste streams to produce recycled 3D printing filament. Thus, also motivating the development of an additive symbiotic network.

Consequently, in the second research phase, case study A was developed to explore and validate the requirements to adopt the blockchain technology in an additive symbiotic network, allowing to answer to the second research question *(***RQ2** *- What are the requirements to make use of blockchain technology in an additive symbiotic network)*. Finally, in the third research phase, case study B was developed to assess the strength of the relationships in the supply chain structure of an additive symbiotic network, addressing the third research question of this PhD research work (**RQ3** - *What are the implications of blockchain technology adoption in the supply chain structure of an additive symbiotic network?).* Hence, case study B also allows to validate the findings from case study A in terms of requirements to adopt blockchain technology.

1.4 Thesis structure

This thesis results from methodological and theoretical explorations within the scope of ISNs in the AM industry. The thesis's s structure is presented in Figure 1-3, highlighting the main theoretical, methodological and empirical steps considered to address the PhD research work objectives and results. The thesis contains six chapters. The first chapter introduces the motivation and aims for this PhD research work and its main objectives.

The second and third chapters present relevant literature regarding the development of ISNs in the AM industry. The second chapter corresponds to phase I of the research approach and includes the results of a systematic literature review to identify what and how wastes are being used in AM processes, contributing to the exchange of resources between industries and, thus, enabling the development of ISNs. In Chapter 2, a proposal of a new concept to the literature is given: the additive symbiotic networks. The chapter ends with a methodology for characterizing the value flows and stakeholders involved in those types of networks.

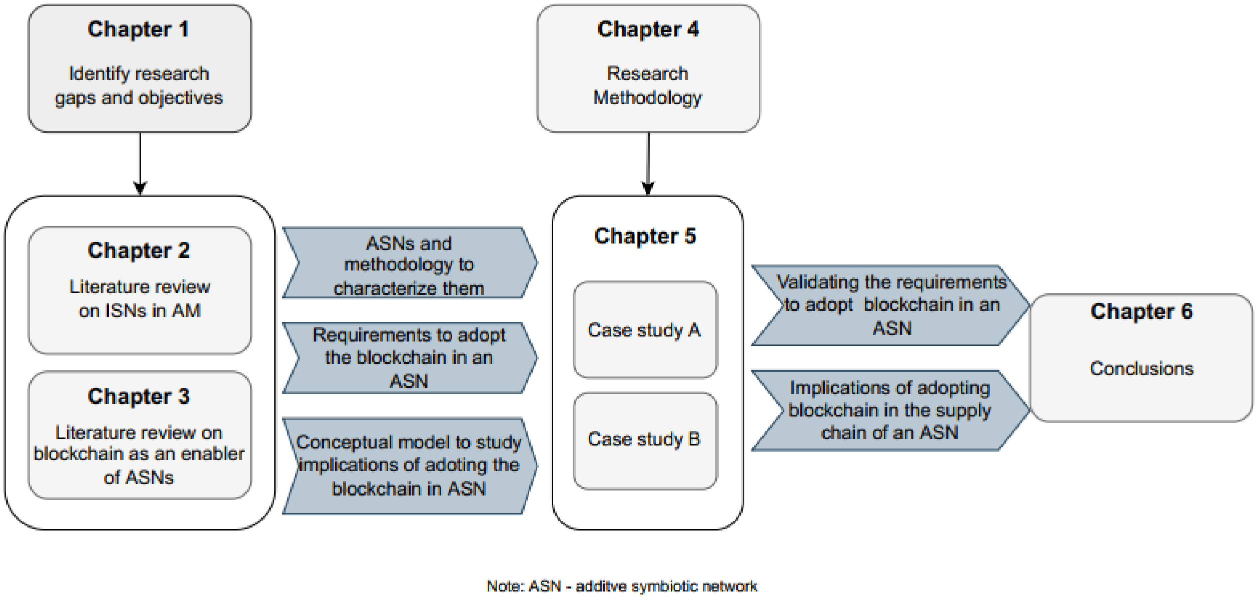


Figure 1-3 PhD Thesis' structure

Chapter 3 introduces blockchain technology as an enabler tool for developing additive symbiotic networks. An overall introduction to the technology and its main characteristics is given, highlighting how adopting such innovative technology could enhance the development of additive symbiotic networks. This third chapter presents a diagram to consider if blockchain technology meets the requirements to be adopted in such symbiotic networks. The chapter ends by giving a conceptual model to understand the implications of adopting blockchain technology in the supply chain structure of an additive symbiotic network.

Chapter 4 introduces the research methodology used and discusses and justifies the main methodological options. Additionally, the criterion for case study selection is presented. This chapter also contains the data collection and the design criteria used to ensure the quality of the case studies.

Chapter 5 presents the data collected during phases II and III of the research approach and presents two case studies. Even though the two case studies were conducted simultaneously, they corresponded to different phases of the research approach and aimed to answer different research questions (as highlighted in the above sub-chapter 1.3). The first part of Chapter 5 presents the data collected regarding the company re:3D (i.e., case study A) and, in this chapter, a value flow matrix that allows the characterization of the networks is created using empirical evidence collected in the case study. The requirements for adopting blockchain technology in the additive symbiotic network from the case under study are explored and validated, following the decision diagram introduced in Chapter 3.

The last part of Chapter 5 presents the findings regarding case study B, which is related to the B-PET company. After the results from case study A supported the adoption of blockchain technology in such additive symbiotic settings, case study B regarding B-PET also aimed to understand the implications of adopting blockchain technology in the supply chain of that additive symbiotic network. A value flow matrix is presented and used to compare two different scenarios (scenario I – "*As-Is*" without blockchain and scenario II – "*To be*" with blockchain).

Finally, Chapter 6 provides a general discussion on the main theoretical, methodological and empirical issues pertinent to the thematic of additive symbiotic networks. The chapter ends with the PhD research's general conclusions and proposes future work venues.

In addition, five appendixes (Appendix A, Appendix B, Appendix C, Appendix D and Appendix E) are included in this PhD thesis, containing the questionnaires used to support the development of the case studies.

1.5 Chapter summary

This chapter provides an overview of the PhD thesis. The research topic, the main objectives and research gaps that this PhD research work intends to fulfil are presented and discussed. The PhD research work focused on exploring the development of ISNs in the AM context and introduced a new concept to the literature: the additive symbiotic networks. The adoption of blockchain technology as an enabler of these symbiotic networks is explored, and the implications of its adoption in the supply chain of those symbiotic networks are analyzed. The research approach used is briefly described. After presenting all the relevant research areas in this chapter, the following chapters will describe the research topic and its findings.

2

INDUSTRIAL SYMBIOSIS NETWORKS AND ADDITIVE SYMBIOTIC NETWORKS

This chapter introduces the literature on additive symbiotic networks. The chapter starts with relevant literature around the industrial symbiosis concept and introduces the ISNs, created as a consequence of the industrial symbiosis relationships. A systematic literature review was conducted and is presented regarding the potential of the additive manufacturing industry to develop industrial symbiosis networks, leading to the proposal of a new concept in the literature - the additive symbiotic networks. Furthermore, this chapter presents models and methodologies to analyze additive symbiotic networks, their main stakeholders, and their relationships. The chapter ends with a proposed methodology for characterizing an additive symbiotic network

2.1 Industrial symbiosis networks

2.1.1 Industrial symbiosis

Over recent years, our planet has been experiencing accelerated environmental degradation and climate change, with material consumption expected to double over the following years and increase by 70% by 2050 of the annual waste generation (Maranesi & De Giovanni, 2020). Land-use changes, unfettered waste and resource extraction, are pushing social-ecological systems towards exceeding adaptation limits and entering new functioning regimes (Kennedy & Linnenluecke, 2022). The overproduction in modern economies that requires a considerable amount of natural resources to meet the growing needs of the world's population and the scarcity of natural resources is highlighted by Nikolaou et al. (2021), as a critical factor impacting the continuity and effectiveness of production and economy. Furthermore, the waste and emissions that have been generated around the world industries are starting to move forward the adoption of circular economy principles (Demartini et al., 2022; Khan & Ali, 2022). The circular economy has become, in this sense, according to Korhonen et al. (2018), a recommended approach to economic growth that is aligned with sustainable environmental and economic development.

To Kravchenko et al. (2020), the circular economy is seen as a radical shift both in consumption and production systems that aims to keep the value of resources in the system and eliminates waste. The circular economy is defined by Morseletto (2020) as an economic model that aims to efficiently use resources through reducing waste and primary resources, closed loops of products, products parts and materials covered by environmental protection. More specifically, the circular economy focuses on returning residual wastes (and other resources) back to production processes through the shift of classical production business patterns from linear to circular (Nikolaou et al., 2021). According to Ritzén & Sandström (2017), the circular economy suggests keeping materials available instead of disposing them in landfill and consequently closing the loop of materials within the product lifecycle to reduce energy demand and resource usage.

In this context, industrial ecology has emerged as a dedicated discipline aiming to improve industrial systems' sustainability profile (Mirata & Emtairah, 2005). Leigh & Li (2015) highlighted that industrial ecology seeks to design and redesign industrial systems to create more efficient interactions mutually within industrial systems and between natural industrial systems considering the principles of biological ecosystems. Industrial systems are defined by Boons & Baas (1997) as an assemblage of the overall industrial processes, which consist of materials, energy and technologies. Some of the features from the biological ecosystems that must be mirrored in industrial systems are (Boons & Baas,1997): i) industrial wastes or/and discarded products should be incorporated in industrial processes; ii) the system should be resilient and varied to recover and engage from unexpected occurrences and iii) energy requirements, waste generation and consumption of scarce resources should be minimized. Overall, for Mirata & Emtairah (2005) the industrial ecology is devoted to improve the sustainability profile of industrial systems and aims at contributing to the sustainable development through: i) facilitating and promoting a critical paradigm shift in the thinking concerning industry (namely ecological relations) and ii) supporting the emergence of cyclical resource flow patterns.

To achieve its circular objectives, the industrial ecology promotes the implementation of different strategies and tools to facilitate the collaboration among supply chain parties – which is the principle of the industrial symbiosis concept (Leigh & Li, 2015). There are several definitions and approaches in the literature regarding industrial symbiosis. For example, Domenech et al. (2019) highlight the industrial symbiosis as a practical method to achieve the closing loop of manufacturing processes, allowing to transform waste from different industries and processes to feedstock other industries. Moreover, Bauman (2001) highlighted that industrial symbiosis is a concept that promotes the usage and interaction of processes and flows within a studied industrial ecosystem. Also, it is considered by Chopra & Khanna (2014) as a mutually beneficial relationship among industries to achieve productive use of by-products and waste. Abreu & Ceglia (2018) concluded that industrial symbiosis falls under the circular economy's principle, being recognized as a strategy to support the transition from a linear to a circular economy

Chertow (2000, p. 314) defined industrial symbiosis as "*engaging traditionally separated entities in a collective approach to competitive advantage involving physical exchange of energy, materials, by-products and water*". The industrial symbiosis concept includes a diversity of practices that link industrial processes in a regional or local industrial system through the exchange of by-products and utility share that occurs between industries, including the reuse and commercialization of waste (Jiao & Boons, 2014; Ferreira et al., 2019). Industrial symbiosis is considered to be a key strategy for the implementation of circular economic systems (Fraccascia et al., 2021) and mainly focuses on the concept of getting and sharing value from waste (Demartini et al., 2022). It is recognized as being able to increase the economic performance of businesses, create more value for the entities involved, reduce energy and material losses, foster eco-innovation and improve the industrial processes' ecological footprints (Mortensen & Kørnøv, 2019). Industrial symbiosis can contribute to achieving specific sustainable goals (Liu et al., 2022) and is mainly concerned with the cyclical flow of resources across networks of companies, focusing on ways that lead to the optimization of resources based on the collaboration between different activities and industries (Domenech & Davies, 2011).

Ponis (2021) highlighted that industrial symbiosis seeks to form inter-organizational networks designated by ISNs. Whenever there is an industrial symbiosis relationship between different industries or sectors, a network of different entities (designated by stakeholders) is formed. In this way, the circularity of materials and other resources is promoted in inter-organizational networks constituted by different stakeholders that continually exchange materials, by-products, and energy, with minimum or zero waste produced (Ponis, 2021). Mirata & Emtairah (2005, p. 994) defined ISNs as "*a collection of long-term symbiotic relationships between and among regional activities involving physical exchanges or materials and energy carriers as well as the exchange of knowledge, human or technical resources, concurrently providing environmental and competitive benefits*". According to Chopra & Khanna (2014), the ISNs are highly efficient regarding resource usage and with substantial environmental and economic benefits to the stakeholders involved. Industrial symbiosis relationships are fostered through a different number of factors that include (Neves et al., 2020): to obtain economic advantages, meet environmental requirements such as the reduction of greenhouse gas emissions, save resources, protect the exploitation of natural resources and reduce the waste that would be otherwise sent to an incinerator or landfill. Furthermore, Mirata & Emtairah (2005) highlighted the potential benefits of developing ISNs, such as:

- Economic benefits emerge from reduced costs related to waste management, resource inputs in production and from generating extra income due to higher values of waste streams and by-products.
- Business benefits are connected to improving relationships with external parties, new markets and products and developing a green image.
- Social benefits are due to the generation of more employment and improving the quality of the existing jobs by creating a safer, natural, and cleaner working environment.
- Environmental benefits arise with the improvement in resource use, pollutant emissions and reduction in the use of non-renewable resources.

By creating a collaborative web of material, knowledge and energy exchanges between different stakeholders, ISNs aim to reduce the production of waste by the industrial sector and the intake of virgin raw materials (Domenech & Davies, 2011), making use of spatial proximity of industrial activities to respond to some environmental concerns through the catalyzation of inter-organizational collaboration among local economic stakeholders to harvest environmental improvements (Mirata & Emtairah, 2005). Xiang & Yuan (2019) highlighted that within ISNs, different stakeholders can interact with each other, such as: companies from distinct industrial sectors or services companies, local entities, governmental/municipal offices, non-governmental organizations, research centres, consumers, suppliers, and others.

In sum, ISNs are defined by all the stakeholders who play an active role in the network and interact with each other, exchanging value directly or indirectly through the sharing of resources that may include material exchanges, informational and knowledge exchanges or infrastructure sharing. In this PhD research work, it is considered by value any beneficial action for the stakeholders engaged in circular economic ecosystems (Ferreira et al., 2019).

Mortensen & Kørnøv (2019) consider three different phases for the stakeholders' engagement in an ISN: i) awareness and interest in industrial symbiosis; ii) reaching out for industrial symbiosis potentials; and iii) organization of new relations and rules' definition. In these three phases, having a platform for interactions between stakeholders provides space for trial and error and motivates a more experimental approach toward the emergence of ISN. Additionally, Yeo et al. (2019) proposed a six-phase framework for industrial symbiosis creation; the functional requirements, the stakeholders involved, and tools to operationalize for each phase are summarized in Table 2-1.

The first three phases of the framework (which corresponds to I – preliminary assessment, II – engage business and III – find synergy opportunities) mainly concern the stakeholders involved in the networks and the exchanges occurring between them. Phase five (V- implementing transactions) relates to the transactions that arise from the stakeholders' exchanges. Järvenpää et al. (2021) showed that there is currently a lack of information to find suitable partners for symbiosis relationships and to check the availability of by-products and waste.

Table 2-1 The industrial symbiosis creation framework. Adapted from Yeo et al. (2019)

Industrial symbiosis (IS) creation phases		Functional requirements	Target stakeholders	Tool requirements
Phase I - Preliminary assessment	- To understand sustainability and local conditions - Analysis of needs and requirements	Collecting intelligence to assess previous streams and regional attributes and to determine the sustainability and potential for creating IS	- Eco-industrial park/estate planners - IS facilitator	- Data from the process input and output - Geo-spatial related data - Statistical data sets - Historical cases of information capture and gathering
Phase II- Engage businesses	- To identify potential members and recruitment - To foster a cooperative culture - To create interest and awareness	- Create awareness and interest - Build trust - Build and grow networks of businesses	- Stated to be utilized via authoritative body or facilitation body - Individual businesses	No specific conditions. The preferred impact of these tools can be improved by relying on success cases that help to illustrate the benefits of IS

Table 2-1 The industrial symbiosis creation framework. Adapted from Yeo et al. (2019) (cont.)

Industrial symbiosis (IS) creation phases		Functional requirements	Target stakeholders	Tool requirements
Phase III - Find synergy opportunities	- Share of Information and collection of data - To find synergy opportunities - Input/out and process analysis	To determine the potential synergetic relations between businesses	- Enterprises with interest in partaking in IS exchanges as utilizers of the platforms and IS administrators as hosts of platforms to match - Partaking organizations in self-driven IS as utilizers of non-platform-based stream matching methods - Network optimization and design: Planners of Eco-industrial estates/parks	- A matching mechanism based on Free market: details such as information on the partaking enterprise, location, textual definitions of waste at the buyer and supplier sides, requirements /availability regarding price, time and quantity. - A matching mechanism based on process input/output stream: company-detailed data regarding the flows of resources, the "wants" and "haves", and specific data - Design and Optimization of the Network: data needed for defining the physical system such as enthalpy, pressure, temperature, flow rate, and chemical types of stream concentration.
Phase IV- Business feasibility	- To analyze cost/benefits - Quality considerations - Regulatory and risk considerations	Offer decision support in selecting and planning for several IS-based options	Partaking organizations in IS exchanges or IS networks	Data needed by economic calculations and methods are freely accessible to be applied.
Phase V- Implementing transactions	- Transaction creation - Environmental, societal and economic impact assessment - Reporting and monitoring	To manage the project, to follow the evolution of the implementation of IS opportunities and to assess the performance	IS orchestrators seeking macro-level information on ISN	- No particular necessities, except for entering data by IS practitioners - Input data necessities by every single performance assessment tool
Phase VI - Reinforcement and Document	- To capture success cases	The overall role of concrete IS cases dissemination of information	- IS orchestrators for indicating potential IS interchange - Organizations of self-driven IS by employing the current documentation for generating new IS ideas	Concrete information which describes the occurrence of IS cases and operating documentation by the tool upholder.

Notes: IS – Industrial symbiosis; IS orchestrators represent facilitators or eco-industrial estate/park planners

Furthermore, the literature regarding models or methodologies to quantify the relationships embedded in an ISN is also scarce.

Thus, considering that ISNs are constituted by a group of stakeholders that participate in or influence the symbiosis relationship, it is critical not only to identify and characterize the stakeholders involved clearly but also the exchange of resources occuring between them.

2.1.2 Using additive manufacturing in circular economy ecosystems

Increasingly nowadays, manufacturing industries are reaching towards closed-loop supply chains and systems, and in this sense, Rajput & Singh (2019a) identified Industry 4.0 to potentially provide opportunities to unlock the implementation of circular economic systems. In another study, Rajput & Singh (2019b) demonstrated that Industry 4.0 enablers provide favourable circumstances to reinforce circular strategies, such as recycling or remanufacturing, and also extend the life cycle and value of products and improve maintainability. Industry 4.0 can be defined as an integration of real-time communication and digital technologies to automate manufacturing systems and achieve precision, accuracy and a higher degree of automatization (Järvenpää et al., 2021; Rajput & Singh, 2019b). According to Tavares et al. (2020), one of the most critical technologies in Industry 4.0 is the AM (or, as commonly designated, 3D printing).

According to the American Standard Testing and Materials - ASTM International, AM can be defined as "*the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies*" (ASTM, 2016). The AM technology is based upon seven principles (Rahito et al. 2019) (described in Table 2-2) and could be deployed in with several main technologies, materials, and different applications (Guo & Leu, 2013).

As a disruptive technology, AM can provide many significant advantages over traditional processes. These advantages include the design no longer limited by conventional machining constraints, elimination of the need for specific tools requirements, allowing the production of small quantities of a customized product and the production of complex shapes from different types of materials (Oettmeier & Hofmann, 2017; Singh et al., 2017). While increasing processes' efficiency, AM technology can replace classical production technologies (Barz et al., 2016). In the design phase of a product, AM allows customers to participate in it, which may result in high levels of customer satisfaction (Faludi et al., 2017). Hence, AM is a highly flexible process that enables a company to be highly responsive to market needs at a minimal cost.

Table 2-2 AM principles and technologies. Adapted from Rahito et al. (2019)

AM principles	Example of AM Technology	Basic Principles
Powder Bed Fusion	Direct Metal Laser Sintering Selective Laser Sintering Melting	Fusion of a specific coordinate in a small region of the powder bed using focused thermal energy.
Direct Energy Deposition	Laser Engineered Net Shaping Plasma Arc Melting Laser Cladding Wire and Arc Additive Manufacturing	Deposition of powder materials that coincides with focused thermal energy to melt it.
Binder Jetting	3D inkjet technology	Liquid printing binder deployed onto specific coordinate, layer by layer of material powder that sticks at the particle.
Sheet Lamination	Laminated Object Manufacturing Ultrasound consolidation Ultrasound	Attachment of sheets of materials.
Vat Photo Polymerization	Stereo Lithography Digital Light Processing	Focused light-curing towards liquid photopolymer resin in a vat.
Material Extrusion	Fused Deposition Modelling Fused Filament Fabrication Fused Granular Fabrication Fused Particle Fabrication 3D inkjet technology	Precipitation of building materials droplets through a heated nozzle.
Cold Spray	Multi-Metal Deposition	Injected powder at high velocity to build material, caused by the adhesion.

According to Ford & Despeisse (2016), a diversity of materials can be used for AM depending on the type of AM process that is going to be used. This includes polymers, ceramics, metals, and sometimes composites (Guo & Leu, 2013). In their review, Bhatia & Sehgal (2021) summarized the main AM materials and applications (Table 2-3). Polymers offer a variety of mechanical and chemical properties that can be used for a wide range of applications (Mikula et al., 2021) and currently play an essential role in the industry due to their specific properties such as: high electrical/thermal insulation, possibility to operate in a wide range of temperatures, good mechanical properties (toughness, ductility, strength-to-weight ratio and stiffness) and corrosion and light-resistance (Vidakis et al., 2020).

Furthermore, Reich et al. (2019) investigated in their study the environmental impact of polymer recycling, stressing out many types of waste polymers that have been recycled into 3D printing filament, such as polylactic acid, acrylonitrile butadiene styrene, polyethene terephthalate or sometimes composites using carbon reinforced plastic.

Table 2-3 AM materials and applications. Retrieved from Bhatia & Sehgal (2021)

Types of materials	AM materials	Applications
Polymers	Acrylonitrile butadiene styrene, Nylon, Acrylonitrile styrene acrylate, High Impact Polystyrene, Polyethylene, Polylactic acid, Polycarbonate, Polyethylene terephthalate glycol, Polyether ether ketone, Thermoplastic polyester, Methyl methacrylate acrylonitrile butadiene styrene etc.	Health care sector, Aviation industry, Automotive industry, Fabrication of toys, Electronics industry etc.
Metals and Alloys	Titanium and its Alloys, Nickel based Alloys, Sterling Silver, Stainless and Tool Steel, Aluminum Alloys, Brass, Copper, Gold, Platinum Bronze etc.	Aerospace industry, Aviation industry, Automotive industry, Health care sector and Defense, etc.
Biomaterials	Biomedical Metal Materials, Biomedical Polymer Materials and Biomedical Ceramic Materials etc.	Health care sector.
Composites	Particle Reinforced Composites, Natural Fiber-Reinforced Composites, Synthetic Fiber-Reinforced Composites, Nanomaterial Reinforced Composites, Ionic Polymer-Metal Composites, Graphene-based Composites and Lightweight Cellular Composites etc.	Production, Electronics, Aerospace, Health care sector, Structural, Sporting, Wearable and Automobiles, etc.
Ceramics	Tape-cast Alumina, Zirconia Green Sheets, Silicon Carbide, Silicon-Silicon Carbide Composite, Glass-Ceramic Composite and Lead Zirconate Titanate etc.	Health care sector, Aerospace, Automotive industry etc.
Building materials	Concrete includes different combinations of sand, cement, hydraulic cements, flyash, micro-fibres, silica fumes, water-to-cement ratios, etc.	Construction industry. Additionally, this technology helps construct complex structures on Moon, Mars and Outer Space.
Food printing materials	Food inks (actively extrudable - confectionery (chocolate, dough), dairy and hydrogels) and non-natively extrudable (meat and plants -fruits, vegetables and algae)	Food Sector, including small scale and industrial scale food production
Smart materials	Enhanced smart nanocomposites, Shape memory alloys, Shape memory polymers, Self-evolving structures, Active-origami, Smart hydrogels, Carbon nanostructures, Copolymers, Viscoelastic ink, Nanoclay, Glucose, Polylactic acid and Graphene, Resins and acrylamide monomer etc.	Aviation industry, Automotive industry, Health care sector, Robotics, Aerospace, Defense, Art and Textile etc.
Other materials	Glass, Wood, Photopolymers or Light Activated Resin and Cellulose Materials etc.	Furniture printing, Textile industry, Health care sector, Electronics industry, and Responsive wearable textiles etc.

According to Reich et al. (2019), upcycling plastic waste into filament for AM processes with an open-source waste plastic extruder is one way to overcome the artificial barrier related to costs in the AM industry, emphasizing that it is possible to eliminate the need for filament and print directly from pellets, particles, flakes, shreds or regrind of recycled plastic. When operating a 3D printer through extrusion, the filament itself is used, reducing the environmental impact and operating costs of the AM equipment (Kreiger et al., 2013). The filament extruder not only allows the production of granulated filament but also has a built-in grinder that supports processing any plastic.

Material extrusion 3D printers that allow printing directly from plastic pellets have been developed over the past few years (Alexandre et al., 2020). Authors like Cruz Sanchez et al. (2015) have highlighted in their study different development initiatives of open-sources small-scale plastic extruders that allow transforming post-consumer waste into filament to feedstock 3D printers, namely: the Recyclebot, the Lyman Filament Extruder and the Filabot. The extruder 3D printer offers the potential to reduce the melt cycles in the fabrication of AM parts from recycled plastic materials and has proven to provide the potential for distributed recycling with an improvement in economic and environmental performance (Alexandre et al., 2020). Currently, waste extruders are being used directly for shredding, preparing and processing waste filament for recycled use (Peeters et al., 2019). For example, the RepRapable Recyclebot is an open-source 3D printing waste extruder that can transform plastic into commercial quality 3D printing filament (Woern et al., 2018). In this sense, Cruz Sanchez et al. (2020) emphasized that AM can be seen as a tool for recycling to reuse plastic waste material, improving resource consumption efficiency. Thus, AM processes can increase the potential to recover the value embedded in plastic waste.

Angioletti et al. (2016) highlighted that several technologies are considered essential enablers for relevant changes in economies and society, emphasizing the role of the AM that practitioners and researchers have seen over the years as one of these critical technologies. AM technologies possess unique characteristics that support circular economy strategies such as: encouraging repair and refurbishment operations, extending the products lifecycle by printing the necessary parts on site and the potential waste reduction and material-input savings (Hettiarachchi et al., 2022). Projects such as RecWoo3D (aclima, 2018), OWA 3D (OWA, 2021) or The Fenix Project (Rosa & Terzi, 2021) demonstrate how AM technology can use recycled materials as material inputs for AM processes.

The alignment between the AM and the circular economy has become widely recognized by practitioners and researchers, with the AM being seen as a promising technology for a more sustainable production that enables the demand production of spare parts for repair or avoids material losses when compared to other traditional technologies, allowing the reduction of the amount of material used from maintenance to re-use, from the rework to recycling and the reduction in the energy consumption (Angioletti et al., 2016; Sauerwein et al., 2019). To Hettiarachchi et al. (2022), the AM enables product customisation and innovation to create personalised products, encourages refurbishment and repair, and extends the product lifecycle through printing the necessary parts for repair or replace broken products onsite. In fact, Hettiarachchi et al. (2022) highlighted that AM processes possess unique characteristics that support circular economy strategies such as: encouraging repair and refurbishment operations and extending the products lifecycle by printing the necessary parts on site and the potential waste reduction and material-inputs savings. Moreover, within the AM context, after exceeding their useful life, the resources can be recycled and recovered, remanufactured or reused, which consequently stands along with the circular economy principles towards the creation of a regenerative economic system that contributes to the reduction of the burden in the environment through the use of resources for as long as possible (Ponis et al., 2021). Additionally, studies like Haleem & Javaid (2019) and Rosa & Terzi (2021) highlighted that the AM contributes to a reduction in waste through recycling processes, thus promoting a reduction in the usage of raw materials. In addition, AM can influence the distribution of manufacturing and flows of goods and materials with many sustainable benefits (Despeisse et al., 2017) since it provides technological features to use a limited amount of materials and energy (not exceeding the quantity needed of materials to produce and create the product) (McDonald, 2016), as well as the fabrication of parts in small-batch sizes reducing the supply chain inventory levels (Yuan et al., 2022).

Currently, some studies are already exploring AM's potential in developing the circular economy concept. AM enables circular design strategies like repair and upgrades that extend a product’s lifespan without these being considered in the original product design. This is due to AM characteristics such as adaptability and digital production. Digital product files can be adapted to change needs or contexts or to enable repair (Sauerwein et al., 2019). The alignment between the circular economy and the AM must take into consideration some aspects which may contribute to the optimization of some circular systems’ phases (for example, for reuse, rework, maintenance, and recycling of products), namely (Angioletti et al., 2016):

- Flexible manufacturing strategies: AM production systems are based on strategies that may support the minimization of transportation needs and can reduce the number of logistics activities.

- Maintenance interventions and hard repair: the spare parts can be manufactured by AM processes only if the necessity of using them arises. This can lead to savings in storage and space costs related to spare parts.
- Material savings: AM enables material savings due to the absence of tooling. Using the almost exact amount of material needed to manufacture the product, AM allows for reducing waste generation and the use of raw materials.
- Design-based economy: AM characteristics may decrease the barriers related to the products and manufacturing process knowledge since parts can be manufactured directly from 3D CAD files without requiring manufacturing expertise.
- Extended product life span: due to the specific technical improvements given by the AM technology and also due to more accessible access to parts' repair interventions instead of manufacturing new parts, the product's life span may increase.

Even though there are increasing opportunities to discuss the intersections between the AM and the circular economy, few recent studies have focused on these intersections (Hettiarachchi et al., 2022). For example, Shanmugam et al. (2020) have explored the opportunities for using recycled polymer (plastic) materials in AM processes and its ability to accommodate a design toward a circular economy. Additionally, Ponis et al. (2021) have identified six main thematic categories such as: remanufacturing, repairing, AM materials, AM methods, reuse and recycling. Moreover, industrial applications of AM technologies are promoting circular production systems by employing recycled and reclaimed materials as inputs for some AM processes (Despeisse et al., 2017). For example, unused powder from the metal AM can be locally filtered and directly reused (Vayre et al., 2012). The percentage of unused power is highly dependent on the power selection and the target application, however, Vayre et al. (2012) stress that up to 95% of the unused metallic power can be reused. Zander (2019) estimates current plastic recycling rates to be approximately 9.5%, with many plastics used in AM material extrusion not being currently recycled. However, the high value of reusing such plastics will likely motivate recycling.

Thus, as demonstrated by Ferreira et al. (2021), AM technology offers much potential for the development of ISNs, due to its ability to incorporate wastes from different within its processes. In this context, managing the quality of the materials-inputs (wastes or by-products) in the AM processes is critical.

The following sub-chapter 2.1.3 explores the potential of the AM industry to develop symbiosis networks.

2.1.3 Waste valorization through additive manufacturing in an industrial symbiosis setting - a systematic literature review

The organization of manufacturing activities is changing with the emergence of new advanced manufacturing technologies. However, as emphasized in sub-chapter 2.1.1, there is a lack of research on the development of ISNs in the AM industry. Thus, in this PhD research work, a systematic literature review around industrial symbiosis and the AM topics was made and published in Ferreira et al. (2021). This sub-chapter was built based on Ferreira et al. (2021) literature review. It describes the methodology used, main results and conclusions.

The primary objective of the systematic literature review was to identify what exchanges of resources may occur and how wastes can be used as material inputs within AM processes in an industrial symbiosis setting. Having knowledge of the existing cases in the literature of waste valorization through AM in an industrial symbiosis setting can foster new synergies through relationship mimicking, that is, knowledge of success cases can lead to similar organizations applying the same concept, although with different details. This issue is of great importance, especially since the stakeholders involved in the symbiosis are compelled to forge a trustful bond. Considering the definitions of wastes and by-products provided by the WFD and highlighted in chapter 1, AM enables systems to recycle and reclaim waste material as material input for productive processes (Peeters et al., 2019), creating a favourable environment for the development of ISNs.

A systematic literature review aims to overcome the perceived weaknesses of a narrative review (Tranfield et al., 2003). In Ferreira et al. (2021), the research design from Tranfield et al. (2003), Denyer & Tranfield (2009), Rousseau et al. (2008) and Correia et al. (2017) was followed (Figure 2-1) which comprised five phases: problem formulation; literature search; evaluation of research; research analysis and interpretation; and reporting results.

a) Phase 1 – Problem formulation

Considering the lack of knowledge about the industrial symbiosis in the AM industry, this literature review aimed to structure the existing knowledge in the literature about the wastes' valorization and exchange of resources within the AM context.

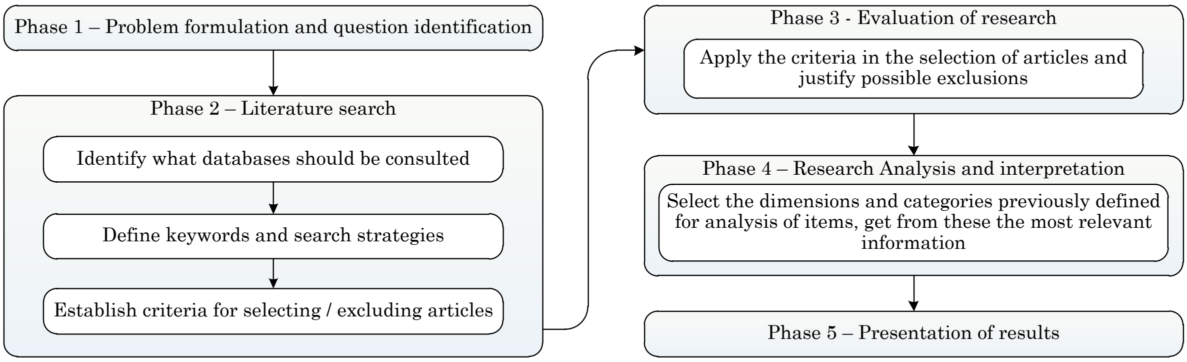


Figure 2-1 Literature review approach

b) Phase 2 – Literature Search

In the second phase, the bibliographic databases, keywords, and search strategy are identified (Correia et al., 2017). Some authors recommend using various sources of information from unpublished studies, conference proceedings, and the internet, e.g. Tranfield et al. (2003). However, following the guidelines of Denyer & Tranfield (2009), only peer-reviewed publications were considered to control the sample quality in this study. Two databases with the highest coverage for the researched topic were considered: "Web of Science" and "Scopus".

The keywords composing the search stream were designed deliberately broad to ensure that articles related to AM and industrial symbiosis were located. Therefore, in a first step, the keywords "industrial symbiosis" and "additive manufacturing" were used. Given the fact that the industrial symbiosis concept is in its very beginning of implementation in the AM industry, no results were found in none of the databases. From this procedure, different combinations of the following keywords were tested "industrial symbiosis", "3D printing", "additive manufacturing", and "symbiosis network". To obtain the broadest sample of documents for analysis, the keyword "industrial symbiosis" was widened, and the keyword "circular economy" was used, which led us to a few studies already conducted on this subject.

The search strategy was to consider documents published from January 2014 until October 2022 and was done in the field "topic" (which includes title, abstract, keywords, and keywords plus) for the database "Web of Science" and by article title, abstract, and keywords for the SCOPUS's database.

c) Phase 3 – Evaluation of research

Five research streams were used in both databases: i) "industrial symbiosis" AND "additive manufacturing", ii) "industrial symbiosis" AND "3D printing", iii) "symbiosis network" AND "3D printing", iv) "symbiosis network" AND "additive manufacturing" and v) "circular economy" AND "additive manufacturing". Only one research stream found results: "circular economy" AND "additive manufacturing". More specifically, 73 results were found for the "Web of Science" database and 92 results from the "SCOPUS" database. The results from the different databases were compared, and the duplicated documents were eliminated. A total of 109 documents were found.

Given the multifaceted nature of the circular economy concept within the AM industry, title and abstracts and, subsequently, full contents of the documents were reviewed for selection.

To ensure that only relevant documents were considered, several inclusion/exclusion criteria were established such as follows: only documents in English were analyzed; all documents which the publication type was defined as books and book chapters were excluded; lastly, documents that did not refer to any of the 4R's from the 4R framework by Kirchherr et al. (2017) - Reduce, Reuse, Recycle, Recover, were eliminated. The resulting documents were read in full to evaluate their focus on possible industrial symbiosis relationships and relevance to the problem formulation. From this process, a final sample of 83 documents was reached.

d) Phase 4 – Research analysis and interpretation

This phase aimed to summarize the information extracted from the sample. In order to analyze the collected information, analytical categories are needed to be created that facilitate the ranking and synthesis of each document (Broome et al., 2000). A set of seven categories, and several subcategories, was used to analyze the documents in the sample, as presented in Table 2-4.

a) Phase 5 – Presentation of results

In this phase, the goal was to analyze in detail the sample contents and provide inputs to the problem formulation. A detailed analysis of the documents was performed (available in Appendix A), according to the defined categories in in Table 2-4.

Table 2-4 Categories and subcategories considered for sample analysing

Category	Subcategories
Document identification	Authors – list of authors Publication date – year of publication Publication type – international journal or conference name Language – English or other
Domain	Research field – may include, among other subcategories such as “Engineering”, “Materials Science”, “Science & Technology”, “Environmental Sciences”
Research methods	Analytical – conceptual (e.g., conceptual models or future research/scenarios)
	Empirical – case studies, content analysis, statistical sampling (e.g., expert panels or surveys), mixed methods, experimental design (experimental empirical design)
	Others
Circular Economy principles - 4R’s (a)	Reduce, Reuse, Recycle, Recover
Industrial symbiosis characteristics (b)	Exchange of resources – it takes the value ”yes” if there is an exchange of some type of resources, or the value ”no”
	Type of resource – it includes waste, sub-product, by-product, raw material, product, energy, residue, material, services, structures, secondary raw material
Type of technology (c)	AM technology – for example, Direct Metal Laser Sintering, Selective Laser, Sintering/Melting, Laser Engineered Net Shaping, Plasma Arc Melting, and 3D inkjet technology, Wire and Arc Additive Manufacturing, among the ones cited in Table 2-2.
Type of material (d)	Materials input for AM processes – it contains the type of the material used in as input for the AM process as it is described in the document
Notes – (a) (Kirchherr et al., 2017); (b) (Kosmol & Esswein, 2018); (c) (Rahito et al., 2019) ; (d) (Guo & Leu, 2013).	

From a total sample of 83 documents, all of them focused at least on one of the 4R’s frameworks that is the core of the circular economy; moreover, it is possible to notice that the ”R” correspondent to “Recycle” is the most common to appear (exclusively 36 documents referred to recycling). This derives from the fact that most of these documents highlight the remanufacturing activity, which is part of the industrial symbiosis concept and can be promoted through the AM. Most of them (64 documents) used empirical research methods using case studies or mixed methods.

Even though the application of the industrial symbiosis concept within the AM industry is in its early beginnings, the systematic literature review provides evidence of the development of the multidisciplinary approach crossing the domains of engineering, materials science, business & economics, decision sciences, physics, chemistry, and environmental sciences & ecology.

In the sample under study, 25 documents explored or even mentioned the possibility of developing ISNs within the AM industry, through the exchange of resources, namely wastes and other materials. From the 25 documents explored, there is a need to highlight that problems concerning the variability of waste composition are not addressed. For wastes that often contain valuable properties in such concentrations, their recovery might be economically viable. As an illustrative example, the analysis of the study from Byard et al. (2019) is presented. For this study, the main findings of current applications of wastes as secondary raw materials or by-products in AM processes can describe in the following way:

- In Byard et al. (2019), it is explored the possibility of using industrial 3D printers capable of Fused Particle Fabrication/Fused Granular Fabrication printing directly from waste plastic streams (external wastes) through the intervention of green fab labs that could act as recycling centres for converting plastic wastes into valuable products for their communities. The authors study the Gigabot X printer, an open-source industrial 3D printer. Acrylonitrile butadiene styrene and polypropylene were the plastic waste streams used for printing three consumer-grade products: a skateboard, kayak paddles, and snowshoes. The results of this study showed that AM technology is capable of producing large, high-value sports products with plastic waste streams.

From analysing this paper, there is evidence that symbiosis networks could be developed in this environment, stimulated by the exchange of resources between entities. For developing and implementing an ISN, there is a need to consider not only the resources that will be exchanged but also to identify the possible stakeholders that would be involved or intend to participate in the network. These stakeholders corresponded to the direct partners that exchange resources directly in the symbiosis network. The indirect partners were not identified at this stage. Additionally, only physical resources (materials or services) were identified:

- In Byard et al. (2019), the origin of the wastes used in the 3D printer (ABS e PP) came from two different entities: Northwest Polymers and McDunnough, Inc., respectively. An intermediary entity allows the incorporation of these wastes in a 3D printer and converts them into consumer-grade products. This intermediary entity is the Green Fab

Lab, which acts like a recycling centre. The products from printing the plastic wastes corresponded to sports mobility products that would be sold to the final consumers. The potential ISN that could be created and developed for this process considers only the three direct partners that exchange physical materials between them. An example of how the initial configuration of the symbiosis network would be is presented in Figure 2-2.

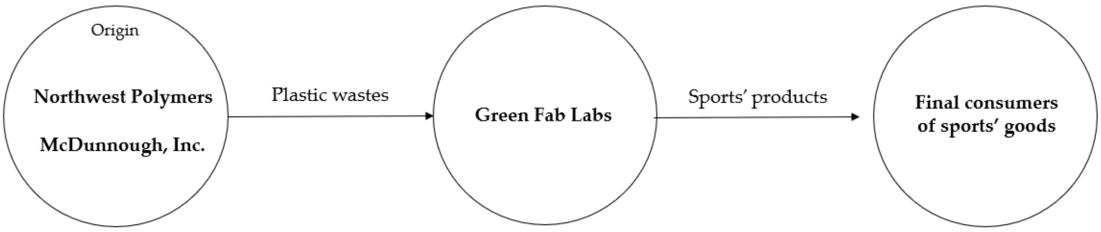


Figure 2-2 ISN formed from plastic wastes used to produce sports goods in Byard et al. (2019)

Similarly, this analysis was performed on all the other documents involved in the sample that explored the possibility of developing ISNs using wastes from different industries as materials inputs for AM processes and technologies. The analysis of the results is presented in Table 2-5.

Considering the 25 documents that focused on wastes' exchange as secondary raw materials or by-products used as materials input for different AM technologies, the most used technologies to incorporate recycled materials referred to fused deposition modelling, fused filament fabrication, fused particle/granular fabrication, selective laser melting, stereolithography, direct energy deposition and sometimes, direct ink writing. In what concerns waste exchanges, most of the commonly used wastes referred in the literature correspond to: plastic polymers (acrylonitrile butadiene styrene and polycarbonate are one of the most used), metal powders, post-consumer waste, scrap feedstock, biological waste (including mussel shells), wool, wood scraps, cork powders, poultry feathers and even, vegetable oils. Thus, this literature review highlights the AM industry's potential to develop ISNs, allowing it to valorize plastic waste streams that other industries may provide as material inputs for its processes.

Table 2-5 Analysis of the papers in the sample under study that explored the potential for developing ISNs

Paper ID	Resume	Potential industrial symbiosis network
Bitting et al. (2022)	Critical challenges in applications of mycelium-based materials as load-bearing structural elements in the construction industry were identified to be used in thermal or acoustic insulation panels. Mycelium-based materials are highlighted as renewable alternatives that use organic agricultural and industrial waste as a critical resource for production and can contribute to a circular economy compared to materials such as steel, concrete, and timber. Other AM technologies identified by the authors that allow to apply mycelium-based materials, such as direct ink writing, fused deposition modelling and bio-ink, can generate either small products (such as furniture, packaging, electronics or building components, such as interior finishing and insulation) or can be applied in architectural projects (examples are given such as Shell Mycelium Pavilion or Monolithic Mycelium Experiments)	From their review, the authors not only explore the existing possibilities of using mycelium-based materials in AM processes but also introduce a new application of these renewable resources that come from agricultural (lignocellulosic such as rice hulls, sawdust, soybean stalks or corn cobs) and industrial waste (such as silica fly ash). In this way, the authors' review supports the development of ISNs where waste from agriculture and plants can be used in AM processes to produce pieces of furniture, packaging, electronics, and in the construction industry can be used as thermal or acoustic insulation panels.
Stefaniak et al. (2022)	The use of waste polymers generated at schools to create feedstock filament to be used in fused filament fabrication AM was explored, with the main goal of characterizing contaminant releases from this process. A distributed recycling process was used to convert waste acrylonitrile butadiene styrene and polylactic acid plastic parts into fused filament fabrication 3D printer filaments. It encompassed two steps: granulation of waste and extrusion of the granules into filament.	The recycling process of using waste polymers at schools to create filament for fused filament fabrication AM is described and characterized. Even though the authors' study aimed to understand the release of contaminants during this process, an ISN can arise from this setting. In this network, the source of waste plastics was fused filament fabrication 3D printed parts from students' design projects that were discarded and, thus, were printed using filament from multiple manufacturers. These plastics (containing acrylonitrile butadiene styrene and polylactic acid) combined with virgin plastics in the form of pellets can produce filament to be incorporated in an AM process to produce the desired outcome.

Table 2-5 Analysis of the papers in the sample under study that explored the potential for developing ISNs (cont.)

Paper ID	Resume	Potential industrial symbiosis network
de León et al. (2022)	The potential of using cork powder used as a by-product from local industries to produce composite materials suitable for fused deposition modelling AM is shown. The cork particles are used along with a polymeric matrix of acrylonitrile styrene butyl acrylate to make the AM processes filaments, allowing valorising residues from other industries.	The potential for valorizing cork dust residues from the sanding process of manufacturing cork stoppers was explored. In their work, the authors used these particles along with acrylonitrile styrene butyl acrylate that was purchased from the company LG Chem to produce filament to be used in fused deposition modelling. Thus, creating much potential to develop an ISN in this context. In this symbiotic network, cork powder can be received as an agro-residue from local industries to be used (along with the adequate polymeric matrix, that in this case can be supplied by the LG Chem company) to produce filament to be incorporated in an AM process. Other stakeholders might be needed to provide the necessary polymers to be incorporated in the 3D printer (in this case, the companies Alfa Aesar and Scharlau).
Pulidori et al. (2022)	An alternative to valorizing poultry feathers waste is presented. In this study, not soluble keratin was obtained as a by-product of a microwave-assisted keratin extraction from poultry feathers. It was combined with polylactic acid pellets to generate a filament for AM, allowing the production of a completely natural, eco-friendly, biodegradable, and biocompatible composite structure.	By introducing the one-pot microwave-based keratin extrusion process, which allows the combination of not soluble keratin from poultry feathers waste and polylactic acid, combined with AM technology such as fused deposition modelling, biostructures can be produced. Thus, giving rise to a potential ISN. In this context, poultry feather wastes can be used as a by-product in an AM process to create biostructures that can be used later on in packaging, agriculture, medicine, and tissue engineering.
de Mattos Nascimento et al. (2022)	A model for circular sustainable AM for scrap recycling in the automotive industry is proposed. A powder is used to serve as material input in a 3D printer to generate new sustainable automotive components using metal scraps as the raw material. Four main steps are required: milling, physical-chemical treatment, 3D printing and mechanical validation tests.	A novel model to support the use of metal scraps from the automotive industry was developed and presented. The model aimed to take advantage of metal parts from automobiles that reach their end of life to produce new parts with identical characteristics to the old ones. From this, a potential ISN could be developed considering the metal scrap waste from the automotive industry. According to the authors, the car is disassembled, and the metal parts are classified according to their characteristics. These scraps can be sold or transformed into metallic powder to be used in metal 3D printers to manufacture metal components (that can be sold later on).

Table 2-5 Analysis of the papers in the sample under study that explored the potential for developing ISNs (cont.)

Paper ID	Resume	Potential industrial symbiosis network
Barkane et al. (2022)	The potential of using vegetable oils as biobased components to formulate the stereolithography resin in AM is demonstrated, highlighting that applying nanocellulose filler prepared from agricultural waste improves the printed material's performance properties.	By highlighting the great potential of using acrylate vegetable oils and nanocellulose fillers as material inputs to produce high-performance resins for a sustainable stereolithography AM, a potential ISN can be implemented. In this symbiotic network, vegetable oils from the agricultural industry can be used as a material input for an AM process to generate a customized final product.
Almonti et al. (2022)	A modular prototype that can be used for thermal storage was developed and thermally characterized. The authors used phase change materials derived from agricultural industry wastes. Phase change materials were integrated into a metallic reticular structure of aluminium and copper to improve the systems' overall thermal conductivity and the heat transfer efficiency.	In this paper, an ISN could be developed considering that the authors use phase change materials that come from agricultural waste (Pure Tempo 68, Crodatherm 60, Crodatherm 74, Crodatherm ME29P). These bio-based materials were integrated with a metallic reticular structure. Hence, from this paper, it is demonstrated that wastes that are made available by the agricultural industry can fill different modulus that are connected and integrated into solar panels with the use of AM to accumulate the heat and work as a heat exchanger and distribute the absorbed energy for different applications (for example, hot sanitary water for domestic use).
de Rubeis. (2022)	The potential of additive manufacturing to produce thermal insulating blocks that are able to increase the thermal resistance of buildings through the reduction of heat losses is emphasized. The authors filled the internal cavities of a 3D-printed thermal insulating block with different recovered waste materials: polystyrene and wool. The main goal was to create a prototype 3D-printed block as a building's thermal insulation, highlighting the role of additive manufacturing in the field of insulating materials and the use of wastes, contributing to the implementation of the circular economy concept.	From this study, a potential ISN can arise using wastes from different industries to fill the cavities of a thermal insulating block printed in a 3D printer. In this symbiotic network, other companies can use wastes such as polystyrene and wool in AM processes (such as fused deposition modelling, fused filament fabrication, stereolithography, and selective laser sintering) to build an insulating 3D printed block. This block can be used later by companies within the construction industry.
Fico et al. (2022)	Different composite filaments based on polylactic acid and amounts of olive wood scraps were fully characterized and compared from a physical, thermal and mechanical perspective, as they are suitable for application in a low-cost 3D printing machine.	There is potential for creating an ISN in which wood scraps from one industry are used to produce recycled filament to be integrated into a 3D printer. Thus, companies with wood wastes could sell these to other companies instead of using polymer raw materials to be incorporated in AM processes (using Fused Filament Fabrication) and to produce a 3D printed object.

Table 2-5 Analysis of the papers in the sample under study that explored the potential for developing ISNs (cont.)

Paper ID	Resume	Potential industrial symbiosis network
He et al. (2022)	The global warming potential and life cycle primary energy demand of an automotive fuel-line clip produced using a recycled waste polymer powder from the AM technology, selective laser sintering, was investigated. This study compared recycled polyamide 12 with conventional polyamide 66. The authors concluded that using recycled polyamide 12 provides a reduction of 8% in the life cycle of global warming potential.	Waste polymer powders produced due to the AM technology selective laser sintering can be subsequently used for injection-moulded components and to make other products. The authors use a real-case application from The Ford Motor Company in this investigation. The company had started to use the degraded polyamide 12 powder from its selective laser sintering process to produce commercial vehicle components, including automotive fuel-line clips. Even though this paper does not mention any type of industrial symbiosis collaboration, an ISN could arise comprising the waste polymer powders produced by one company that uses selective laser sintering as a material input to another company that would replace the virgin polyamide 66.
Stratiotou Efstratiadis & Michailidis (2022)	The role of recovery and recycling waste electric and electronic equipment is explored. These types of wastes can be used as additives to produce filaments for synthesising composite materials employed by AM applications (namely by the fused deposition modelling technology).	Waste streams from waste electric and electronic equipment can be used to produce AM filament. Three waste electric and electronic equipment types were analysed: printed circuit board, thin-film photovoltaic cells and wind turbines. Thus, this study supports the possibility of creating an ISN in these contexts. In this potential symbiotic network, critical raw materials that derive from companies that produce waste electric and electronic equipment (such as printed circuit boards, thin-film photovoltaic cells or wind turbines) can be used by other companies as additives to produce filament to be used in fused deposition modelling AM.
Devarajan et al. (2022)	The potential of printing a nanopowder from nonsegregated waste to generate conventional components is highlighted. A system that converts nonsegregated waste material (such as food, plastics and e-waste) into the synthesized dough, comprising a chamber (that dispenses the nonsegregated waste material), an ultraviolet disinfectant unit (that removes the harmful germs and water content to form solid waste), a shedder (which powder the solid waste) and a storage unit (that stores de powdered solid waste to be mixed later on with components in a mixer to form a synthesized dough) is presented. The synthesized dough can be used in a 3D printer to produce the desired final component.	Even though this did not mention any specific type of industrial symbiosis collaboration between industries, this study supports the development of an ISN by highlighting the possibility of using nonsegregated waste to generate new components through AM. In this network, one organisation's food waste, plastic waste, or e-waste can be transformed into powdered solid waste to be used in a mixer with binders (such as silicone oil) to form a synthesized dough. This synthesized dough can be used by other companies in their 3D printers as a material input to produce the desired parts.

Table 2-5 Analysis of the papers in the sample under study that explored the potential for developing ISNs (cont.)

Paper ID	Resume	Potential industrial symbiosis network
Ordoñez et al. (2022)	Electric arc furnace steel dust waste can be used as a by-product material for kaolin-based clays produced with AM via direct ink writing technology. The combination of clay with steel dust positively contributes to the environment. The authors evaluate using electric arc furnace steel dust as an admixture for clay ceramics to produce 3D printed components. Thus, contributing to the valorization of electric arc furnace steel dust hazardous waste as a material for AM.	Through the valorization of electric arc furnace steel dust waste as a material input for AM technologies, an ISN can potentially arise. In this symbiotic network, one company's electric arc furnace steel dust waste can be used as a by-product (along with ceramic clays) to produce AM products.
Kromoser et al. (2022)	The fabrication of AM of fully recyclable walls made of compositive renewable secondary resources is analysed and discussed. In this paper, a new fully bio-based material concept is introduced, using a combination of lignosulfonate, starch and wood participles (lignosulfonate and wood particles coming from side streams of the paper and wood industry).	A potential ISN could be further developed considering waste side streams from the pulp and wood industry to be used as materials inputs by another industry for 3D printed bio-based walls, allowing the creation of fully recyclable walls for buildings.
Shiferaw & Gebremedhen (2022)	The possibility of using recyclable polymers in fused deposition modelling process is highlighted. These polymers are converted into filaments, and the final products can be printed. In fused deposition modelling, thermoplastic polymers are used as raw materials, which are extruded into filaments and used as feedstock.	The process needed for converting plastic waste into filament that is subsequently processed as AM products is highlighted, giving rise to the possibility of creating an ISN. Plastic waste can be collected and sold in this symbiotic network from other industries, local authorities, or major retailers. These wastes can be used by organizations resorting to fused deposition modelling AM technology. After collecting, sorting is needed to separate the waste by grade and type while removing the presence of impurities. The sorted plastic wastes are cut into pieces, cleaned and added with additives, and extruded to form filaments for the fused deposition modelling. These filaments can be used by the organization itself or can be sold to others.
Ferreira et al. (2021)	A systematic literature on waste valorization by the AM industry was performed. The authors identified what type of resources could be exchanged and how wastes could be used by the AM. From the documents analysed, only 5 of them referred to the possibility of incorporating plastic wastes, scrap feedstock and mussel shells as materials inputs for AM processes.	The potential ISNs highlighted in this review are: i) plastic wastes streams from one company can be used to produce sports goods; ii) mussel shells waste can be used to produce ceramic-like material (e.g. a flowerpot); iii) recycled plastic regrind from one company can be used by other to produce, for example, a mould for rapid moulding; iv) scrap feedstock from one organization can be transformed in powder and be used by another company in an AM process and v) recycled materials from different companies can be used by others as materials inputs for AM processes.

Table 2-5 Analysis of the papers in the sample under study that explored the potential for developing ISNs (cont.)

Paper ID	Resume	Potential industrial symbiosis network
Laoutid et al. (2021)	The development of polymeric composite materials containing tire rubber waste generated from the automotive industry by fused deposition modelling was evaluated as an approach for recycled used tire recovery, thus conferring new applications of the printed composites. The recycled tire rubber waste is used as an additive to produce thermoplastic composite materials among with the host polymers acrylonitrile butadiene styrene and thermoplastic polyolefin.	Through the valorization of tire rubber waste from the automotive industry, as highlighted by the authors, a potential ISN could be created. Using a real case from the study, in this symbiotic network, waste from the automotive industry (provided by the company Rubber Gree) can be used as a secondary raw material for other industries that use fused deposition modelling AM. Other industries and companies can incorporate this type of waste into acrylonitrile butadiene styrene and thermoplastic polyolefin polymer matrices for producing filaments suitable for fused deposition modelling to create AM products.
Häußler et al. (2021)	A closed-loop recycling approach for polyethylene-like materials suitable for high-quality applications was developed. Through chemical recycling of plant oils, via depolymerization to monomer polyethylene-like polymers can be used for injection moulding or 3D printing as a complementary manufacturing method.	Renewable polycarbonates and polyesters in a polyethylene chain can be recycled chemically with a recovery rate of more than 96% and can be incorporated in an AM process. From this, a potential ISN could be developed in which plastic wastes from one industry's post-consumer sorted polymers ('mechanical recycling) can be used by another, resorting to fused filament fabrication AM.
Maldonado-García et al. (2021)	The utilization of ocean plastics with agro-industrial biomass to develop complex-shaped value-added prototypes through fused filament fabrication AM is highlighted. The plastic wastes are used to produce elliptical gears with shafts and a spectacle frame.	Recycled ocean polyethylene pellets and recycled ocean polypropylene from the company Ocean-works USA are used in this study. The waste soy hulls were collected from the company Niewland Feed & Supply Ltd., located in Elora, Canada. In this sense, an ISN could arise within companies producing recycled ocean polyethylene and polypropylene pellets to be used by companies working with fused filament fabrication AM technology to make, for example, elliptical gears with shafts or spectacle frames.
Bergonzi & Vettori (2021)	The influence of using pure and recycled polyethylene terephthalate glycol to produce filament using fused deposition modelling was analysed. Using this AM technology (that resorts mostly to thermoplastic polymers) and with a suitable extruder, waste materials can be melted and incorporated to obtain new filaments.	It is possible to produce new filament from waste from the AM technology fused deposition modelling, thus adding value in terms of the quality of the recycled polymer. Two start-ups conducted experimental studies on polyethylene terephthalate co-polyester filament from pure and material transformed through fused deposition modelling technology. From here, a potential ISN could be developed between organizations that resort to fused deposition modelling technology (and generate wastes from this process) and organizations that need filament for 3D printers. The organizations selling the waste streams can also produce and use the filament for their benefit.

Table 2-5 Analysis of the papers in the sample under study that explored the potential for developing ISNs (cont.)

Paper ID	Resume	Potential industrial symbiosis network
Reich et al. (2019)	This study explores the potential of using recycled polymers in 3D printing, namely in fused particle fabrication or fused granular fabrication. The authors analyzed one of the possibilities to overcome the artificial cost barrier to distributed AM through the upcycled of plastic waste, namely polycarbonate plastic regrind, into 3D printing filament with an open-source waste plastic extruder (designated by Recyclebot). Three case study applications were explored: i) using polycarbonate waste to successfully manufacture it into a mould that can be used for rapid moulding, ii) using a home floor steamer whose outer plastic has become brittle and disintegrated, allowing to print a new steamer head and iii) an open-source car window ice scraper with interchangeable blades. The handle was printed via polylactic acid, and the blade was printed on a recycled PC.	From this study, a potential ISN could be developed in this setting. In this case, the entity responsible for providing the recycled polycarbonate regrind as the waste to be incorporated was McDonnough Plastics. Companies or organizations that work or own a Gigabot X printer buy from McDonnough and use these polymers to produce filament. Consequently, this filament in this symbiotic network can be used internally or sold to other companies working with AM technology.
Sauerwein & Doubrovski (2018)	An approach is developed to support the search and use of local materials as material input for AM. The authors explored the possibility of adapting mussel shells waste into AM material. Mussels' shells can be considered waste unsuitable for composting and printing mussel shells waste results in a ceramic-like material; therefore, a flowerpot was considered a suitable initial product application to demonstrate the current applicability.	It is highlighted that approximately 50 million kgs of mussels are produced in the Netherlands. The shells of the mussels are wastes originated by the mussels' breeders. These wastes can be used as materials input by entities or companies that use a binder jetting AM process, creating the potential for developing an ISN. In this network, the companies that have adequate AM technology are responsible for the necessary treatment of the wastes before incorporating them into AM processes. By the end of the process, since the mussel shell print mainly consists of calcium carbonate, ceramic-like materials can be printed (for example, flowerpots can be produced).
Woern & Pearce (2018)	The open-source Gigabot X printer is used to develop a method to optimize Fused Particle Fabrication or Fused Granular Fabrication for recycled materials. The authors analyzed and compared virgin PLA pellets with recycled polymers. The results showed that the Gigabot X and similar printers might use a wide range of recycled polymer materials with no significant post-processing.	In the study, recycled polymers in a 3D printer that came from different entities are used, namely: Nature Works LLC, McDonnough Plastics, Northwest Polymers and CiorC. These polymers can be used as material input by other entities that work or own an open-source Gigabot X printer - a large-scale recycled plastic 3D printer, supporting the creation of a potential ISN. A large variety of polymers from this process can be printed at a lower print time compared to the traditional Fused Filament Fabrication process. These polymers can then be used internally or can be sold to other entities.

Table 2-5 Analysis of the papers in the sample under study that explored the potential for developing ISNs (cont.)

Paper ID	Resume	Potential industrial symbiosis network
Reijonen et al. (2017)	The circular economy concept is highlighted by recovering metallic scrap generated in the AM process to the feedstock material for selective laser melting. Powder from 100% scrap feedstock was prepared using two different routes, and the properties of the powder were tested and analyzed to determine the mechanical properties and compared them to commercial reference powder. The study showed recycled powders' properties that are entirely comparable to the reference could be reached.	This study focused on the recovery of process side-streams back to feedstock material. In fact, there is not an ISN inherent to this process. However, supposing other entities that use selective laser melting as the AM processes would have interest in it. In that case, a potential ISN could arise in which the entity responsible for generating the waste and incorporating the process side-streams into feedstock material could, later on, sell the service to other organizations or even use the waste stream from other entities.

2.2 Characterizing additive symbiotic networks

As demonstrated in sub-chapter 2.1.3, there is potential to rethink how raw materials are processed to minimise the resources needed to be used as material input for AM processes. Furthermore, Despeisse et al. (2017) highlighted that at the end-of-life stage of a product, recycling systems could be connected to AM, diverting materials from waste streams into new applications and promoting the use of by-products, such as production wastes that can be used as material input for production processes. In an industrial symbiosis setting, the resources exchanged can be categorized as wastes, energy, by-products, materials, services, structures, products and raw materials (Kosmol & Esswein, 2018).

Thus, given its potential to promote sustainable concepts through repairing and remanufacturing activities and reduction in the production of waste (Kravchenko et al. 2020), AM is seen as an enabler for circular economy strategies toward sustainability, including the development of ISNs in this context.

In this PhD research work, the additive symbiotic networks definition is:

> **Additive symbiotic networks** can be understood as ISNs in which wastes or by-products from other industries are used in AM processes as material inputs. These networks can be understood as value networks constituted by several stakeholders exchanging resources between them.

The additive symbiotic networks are expected to have the same benefits and challenges as highlighted in the studies mentioned earlier for ISNs. Considering the novelty of this concept, there is a need to explore existing models and methodologies in the literature around industrial symbiosis to understand how to analyze additive symbiotic networks, their stakeholders, and the main exchanges between them. Thus, literature related to ISNs was adapted to the additive symbiotic networks' context in the following sub-chapters.

2.2.1 Additive symbiotic networks and the stakeholder theory

To develop and integrate the industrial symbiosis strategy, it is necessary to create and develop networks of stakeholders that exchange resources between them. Like the ISNs, the additive symbiotic networks are also formed by a group of stakeholders representing different companies or organizations exchanging resources between them. Considering the lack of existing models to analyze symbiotic networks, it is critical to adopt existing theories, methods and methodologies to identify the stakeholders' roles and their power within symbiotic networks.

According to Freeman & Mcvea (2001), the concept of "*stakeholder*" started to gain relevance in 1984 in Edward Freeman's book *Strategic Management: A Stakeholder Approach Strategic Management: A Stakeholder Approach* (Freeman 1984). Since then, a new field in strategic management called the "Stakeholder Theory" has been advanced, explaining how business work at its best and how it could work. Donaldson & Preston (1995) divided the research around the stakeholder theory into three main categories, corresponding to: i) descriptive stakeholder theory (which relates to the stakeholders' cooperative and competitive interests); ii) instrumental stakeholder theory (which relates to the connections between stakeholder management and the achievement of different corporate performance objectives); and iii) normative stakeholder theory (relates to the stakeholders' interests in procedural or substantive corporate aspects).

However, Freeman et al. (2010) argued that the stakeholder theory should be inherently managerial, highlighting three main problems that the theory has helped to address, namely: i) problem of managerial mindset, related to defining and comprehending what to teach to managers and students about what are the key-resources-actions to be successful in the actual business world; ii) problem of value creation and trade, related with how to comprehend and manage a business in the 21st century where many changes in business relationships occur and these relationships depend on the national industry, policies, and societal context; and iii) problem of ethics of capitalism, related with questions of sustainability, ethics, and responsibility within the usual economic view of capitalism.

Moreover, Freeman et al. (2010) highlighted that, for example, if the stakeholder theory is about value creation and trade, it must show how business can be described by considering stakeholder relationships. Or, if the theory is to solve the problem of managerial mindset, it must adopt a practical way of connecting ethics and business in a way that can be implemented in the real world. Considering these three main problems, and to contribute to stakeholder research in the strategic management field, Feng (2013) proposed three significant opportunities (mainly focusing on the first and second problems): Stakeholder Salience; Stakeholder Network Model and Stakeholders and Strategic Issues. This last point is related to the nonmarket environment, which within this work relates to the indirect stakeholders that also composed the symbiotic networks, but within the scope of this PhD research work was chosen not to be considered. A definition of the direct and indirect stakeholders that are involved in an additive symbiotic network is going to be further detailed in this section.

a) Stakeholder Salience

To address the first challenge of the stakeholder theory, which is to identify an organization's stakeholders, Freeman (1994) suggested using the principle "*Who and What Really Counts*". However, Feng (2013) highlighted that there was little agreement on this principle and to overcome this matter, emphasizing the study of Mitchell et al. (1997) that developed a descriptive theory of Stakeholder Salience. Mitchell et al. (1997, p.854) defined the theory as "*the degree to which managers give priority to competing stakeholder claims*" and can be determined by managers' perceptions of three key stakeholders' attributes:

- **Urgency:** The stakeholder's degree claimed call for immediate attention.
- **Power:** Entity A can get entity B to have something done that entity B otherwise would not do.
- **Legitimacy:** Regarding a social system constructed by norms, values, definitions and beliefs, the actions of an entity are desirable or appropriate.

Through the combination of these three previously defined attributes, Feng (2013) generated seven categories of stakeholders (Figure 2-3) arguing that it is more appropriate to consider the unit of analysis for the Stakeholder Salience Theory as the relationships between stakeholders than the stakeholders themselves.

b) Stakeholder Network Model

Once we consider the stakeholder relationships as the unit of analysis, the next question arising is about how to develop a model to describe those relationships between the stakeholders for informed decision-making. Rowley (1997, p. 887) firstly introduced and applied the Social Network Analysis to construct "*a theory of stakeholders influences, which accommodates multiple, independent stakeholder demands and predicts how organizations respond to the simultaneous influence of multiple stakeholders*". Later on, Feng (2013) chose to classify the development of modelling modern firms and their stakeholders into five stages, from the earliest to the latest:

- The Production Model – also known as the Input-Output Model.
- The Managerial Model – corresponds to the Mental Model shared by firms' managers.

- The Stakeholder Model – constructed by Freeman (1994).
- The Single-Relational Stakeholder Network Model – referred to as the Social Network Analysis.
- The Multi-Relational Stakeholder Network Model – referred to as the Stakeholder Value Network.

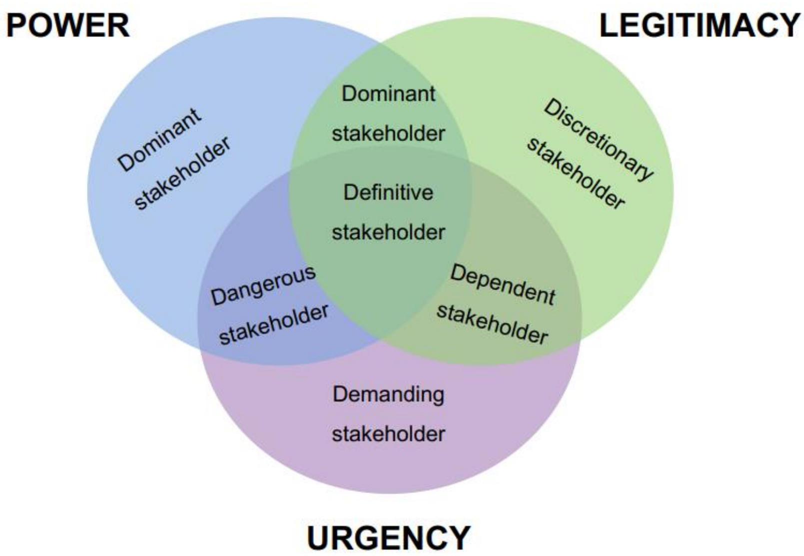


Figure 2-3 Stakeholder Typology. Adapted from Feng (2013)

Still, according to Feng (2013), it is possible to conclude that the models have become more sophisticated, especially in terms of the number of stakeholders included and their relationships as well as their context, for example, the progress from the Stakeholder Model to the Network Model reflects the actual trend of moving from the actors to the network relationships between those actors in terms of "unit of analysis".

2.2.2 The stakeholder value network

To unify both economic and social relationships in one common framework, Feng (2013) highlighted two possible approaches that had been developed over the years: the New Economic Sociology, which corresponds to the social network analysis and the social exchange theory. While the social network analysis studies single-relation networks (meaning that at each time of analysis, only one type of relationship is allowed) without restrictions on the network structure (Oliveira & Gama, 2012), the second approach - the social exchange theory, uses economic exchange models to study different social situations and begins with economic relationships (Cropanzano & Mitchell, 2016). This approach studies multi-relation networks where multiple types of relationships may be considered at each time and with Restrictions on the network structure.

According to Feng (2013), the social network analysis views stakeholders' relationships as empty social ties and studies the impacts of network structures on the stakeholders' behaviour. Reed et al. (2009) highlighted that social network analysis uses numbers to represent the presence or absence of a tie between stakeholders and to represent the relative strength of that tie. These numbers are then represented in a matrix that characterizes a unique relationship, and within this approach, data is typically gathered through structured interviews, observations or questionnaires.

Therefore, social network analysis allows to capture not only different types of relationships but also the strength of those relationships and uses this information in a quantitative form that makes it easier to summarize and analyze. This theory provides a methodological and theoretical framework that aims to advance understanding of the social aspects surrounding an ISN. Thus, an additive symbiotic network can likely shed light on issues such as the process of transferred information, the role of different members in the network, material exchange negotiation, alliance formation and trust building (Domenech & Davies, 2011). The strength of the social network analysis theory relies on providing a method to quantify the structural properties of the whole network, as well as the structural positions of individual stakeholders, allowing to identify which stakeholders are more central and which are marginal and how stakeholders cluster together (Reed et al., 2009). For example, the social network analysis is one technique applied to Kalundborg eco-industrial park to understand its organizational framework (Chopra & Khanna, 2014). In their study, Ferreira et al. (2019) highlighted that the Kalundborg eco-industrial park in Denmark is one of the first examples of a paradigmatic case of a self-organized network that was encouraged to be created due to water scarcity for the manufacturing industry in that geographic area. Later on, the reuse of steam, energy and heat created great chances for the companies or firms to collaborate with each other, forming the Kalundborg Industrial Symbiosis – an eco-industrial park.

On the other hand, researchers and scholars have largely used the social exchange theory to explain business-to-business relational exchanges (Lambe et al., 2001). The social exchange theory is seen as a broad conceptual paradigm that covers many social scientific topics (such as anthropology, management and social psychology) and is not a single theory but rather a family of conceptual models (Cropanzano et al., 2017). One of the basic cores of this theory is that it relates to relationships that evolve over time into loyal, mutual, and trusting commitments. To do so, the entities involved must accomplish certain exchange rules (Cropanzano & Mitchell, 2005). The theory is highlighted by Lambe et al. (2001) as a theoretical explanatory mechanism. Therefore, the use of the social exchange theory is framed based on the exchange rule that the researcher counts on. Considering a symbiotic setting, the social exchange theory could be applied to establish and understand the rules for the exchanges between the stakeholders involved. However, one of the most critics related to the social exchange theory, according to Cropanzano et al. (2017), has to deal with its lack of sufficient theoretical precision and therefore has minimal utility. More precisely, researchers or scholars that apply the social exchange theory may explain many social phenomena in *post-hoc* analysis. Still, they are highly restricted in their ability to make useful *a priori* predictions regarding behaviour.

Feng (2013) highlighted that neither of these approaches was able to simultaneously analyze the multiple types of inter-organizational relationships, and in order to overcome this weakness, the author developed a new network approach that integrates multiple types of stakeholders' relationships, both at the economic and social level. This new approach aimed to study the strategic implications of the exchanged value through the stakeholder network, which is called the stakeholder value network. The Stakeholder value network has its background framed from the social exchange theory, and Feng (2013, p.64) formally defined this approach as "*a multi-relational network consisting of a focal organization, the focal organization's stakeholders, and the tangible and intangible value exchanges between the focal organization and its stakeholders, as well as between the stakeholders themselves".* There are two generic patterns for the exchange of value in the approach of Feng (2013): i) "Restricted exchanges" which comprise the dyadic reciprocal relationships between two stakeholders and ii) "Generalized exchanges" that cover the unambiguous reciprocal relationships between at least three stakeholders involved in the exchange. In this PhD research work, only the restricted exchanges were analyzed, considering the relatively small number of stakeholders involved in the case studies networks.

Feng (2013) highlighted that this network analysis has three objectives that must be accomplished:

- Data Collection – through information collection from interviews and documents.
- Qualitative model – through mapping stakeholders' needs (so-called "value flows") by information collected from articulating stakeholders' needs.
- Quantitative model – through conducting a rigorous network analysis using defined network measurements and network statistics from this analysis.

Initiated by Cameron (2007) and developed by Sutherland (2009) and Feng (2013), the methodological framework of the stakeholder value network consists of four steps:

- **Mapping:** the focal organization should be defined (its roles, objectives and specific needs), along with its stakeholders. This can be a company, a government agency, a non-government organization, a project within a company, or any other type of organization. The focal organization is responsible for conducting feasible negotiations, investigations and regulates the symbiosis' operationalization and implementation. Based on this information, a qualitative model of the stakeholder value network can be constructed in the form of stakeholder maps (which map the specific needs of each stakeholder as a value flow).
- **Quantifying:** after having the stakeholder maps, there is a need to score the value flows and define the propagation rule of value flows in the network. Then, it is needed to calculate the score of each value path.
- **Searching**: stakeholder value network quantitative model can be built based on the quantified value flows and the value propagation rule. The main objective here is to search for all the value paths beginning and/or ending with the focal organization.
- **Analysing**: it is needed to define network measurements and construct network statistics to study the strategic implications of the stakeholder value network for the focal organization.

Within the stakeholder value network approach, mapping the stakeholders within a network is one of the first and most critical steps to include in the analysis. The aim is to develop a qualitative model which includes the stakeholders' roles, objectives and needs and then map their specific needs as value flows (Feng, 2013). These stakeholders' maps are essential because they allow a comprehensive description of the stakeholders within a network and the direct and indirect relationships between them. Hence, to identify a manageable list of stakeholders, information available and collected from news, reports, websites, stakeholder policies and strategy documents, as well as multi-round interviews should be used. The following sub-chapter will present different tools for analysing stakeholders as well as the relations between them.

2.2.3 Tools for identifying stakeholders, differentiating and investigating the relationships between them

As mentioned in the sub-chapter 2.1.1, the first three phases of the symbiosis creation process, for both ISNs and additive symbiotic networks, are related to the local conditions (needs and requirements) for developing symbiotic relationships and to identify potential stakeholders that aim to participate in those relationships, creating interest and awareness. Thus, the need to identify the stakeholders involved in additive symbiotic networks is evident. When analysing stakeholders' needs, Sutherland (2009) developed a list of common characteristics, namely:

- Awareness of a need
- Urgency in fulfilling a need
- The intensity of a need
- Competition in fulfilling a need
- Source's importance in fulfilling a need.

According to Reed et al. (2009), identifying stakeholders is usually an iterative process during which additional stakeholders are added as the analysis is done. The authors made a summary (Table 2-6) of different methods to identify stakeholders and the methods' main strengths and weaknesses. They also proposed a framework to categorise methods for identifying and differentiating stakeholders, categorising stakeholders, and investigating relationships between them. It is noteworthy that some methods may be applied for different purposes – the social network analysis, for example, is mainly used to investigate relationships between the stakeholders; nevertheless, it also can be used to categorise them.

Table 2-6 Methods to identify stakeholders. Retrieved from: Reed et al. (2009)

Method	Description	Strengths	Weakness
Focus groups	Small group brainstorm for: stakeholders, respective influence and interests, other attributes, and categorise them.	- Possible to have consensus over categories of stakeholders - Rapid cost-effective - Adaptable - Useful for generating data on complex issues that require discussion to develop an understanding	Less structured than other alternatives, therefore, it needs effective facilitation to get good results

Table 2-6 Methods to identify stakeholders. Retrieved from: Reed et al. (2009) (cont.)

Method	Description	Strengths	Weakness
Semi-structured interviews	Interviews with a cross-section of stakeholders to check focus group data	- Useful for in-depth insights about stakeholders' relationships - Useful for triangulate data collected in focus groups	- Time-consuming - Costly - Difficulty in reaching consensus about stakeholders' categories
Snowball sampling	Individuals from initial stakeholders' categories are interviewed and identify new stakeholders' categories	- Easy to secure interviews without data protection issues - Fewer interviews declined	Sample may be blazed by the first individual that starts the snowball sampling
Interest-Influence matrices	Stakeholders are placed in a matrix according to their interests and influence	- Possible to prioritise stakeholders for inclusion - Allows to make power dynamics explicit	- Prioritisation may marginalise certain groups - Assumes that stakeholder's categories based on interest-influence are relevant
Stakeholder-led stakeholder categorisation	Stakeholders themselves categorise stakeholders into categories that they created	- Useful for in-depth insights about stakeholders' relationships - Useful for triangulate data collected in focus groups	- Different stakeholders may be placed in the same category and, therefore, turning categorisation meaningless
Q methodology	Stakeholders sort statements drawn for concourse according to how much they agree with them. The analysis allows identifying social discourses	- Different social discourses can be identified - Individuals can be categorised according to their "fit" within the discourses	It only identifies discourses exhibited by the interviewed stakeholders
Actor-linkage matrices	Stakeholders are divided into a two-dimensional matrix, and their relationships are described using codes	- Relatively easy - Requires few resources	- Possible to become confusing - Difficult to use when there are many linkages described
Social Network Analysis	Identifies the network of stakeholders and measures relational ties between stakeholders through the use of structured interview/questionnaire	- Gives insights into the boundary of the stakeholder network - Identifies influential and peripheral stakeholders	- Time-consuming - Needs specialists in the method - Questionnaire may be tedious for the respondents

Table 2-6 Methods to identify stakeholders. Retrieved from: Reed et al. (2009) (cont.)

Method	Description	Strengths	Weakness
Knowledge mapping	Used in conjunction with social network analysis and involves semi-structured interviews to identify interactions and knowledge	- Identifies stakeholders that would work well together as well as those with power balances	- Knowledge needs may still not be met due to differences between the types of knowledge held and needed by stakeholders
Radical transactiveness	Snowball sampling to identify fringe stakeholders and development of strategies to address their interests and concerns	- Identifies stakeholders and issues that might be missed - Minimizes future projects' risks	- Time-consuming - Costly

2.2.4 A methodology for characterizing additive symbiotic networks

Considering the literature presented so far and the lack of research on additive symbiotic networks to map and study the different stakeholders who are part of the network as well as the relationships between them, this PhD suggests adopting the methodology from Ferreira et al. (2019). In their work, Ferreira et al. (2019) applied the approach developed by Hein et al. (2017), using the criteria proposed by Feng (2013) to propose a methodology to characterize ISNs. This methodology assesses the power distribution among the symbiotic stakeholders. The methodology is adapted to the additive symbiotic network context in this PhD research work. Thus, in this context, it aims to explore the power distribution among the stakeholders involved in terms of control over resources, allowing to clearly understand the power of specific stakeholders (Hein et al., 2017).

The chosen methodology (Figure 2-4) allows two main objectives: to identify the most powerful stakeholders within a specific ISN setting and the key resources that contribute to the power of a particular stakeholder in that specific ISN.

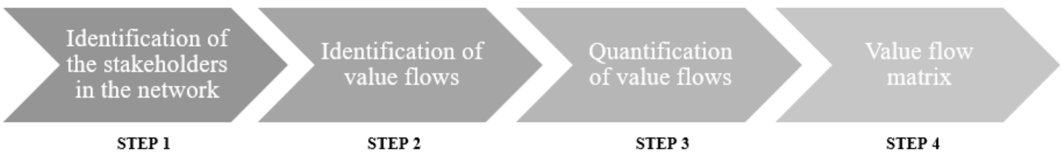


Figure 2-4 Methodology to analyze an additive symbiotic network. Adapted from Ferreira et al. (2019)

The methodology consists of a four-steps as described next:

- **Step 1 – Identification of the focal organization and the stakeholders involved in the network.** This first stage, similarly to the stakeholder value network presented in sub-chapter 2.2.2, consists in identifying the focal organization – the main's responsible for operationalizing and implementing the symbiosis network. After having identified the focal organization, it is possible to proceed with the identification of other potential or already existing stakeholders. Ferreira et al. (2019) distinguish between two main types of stakeholders: direct partners - the ones directly involved or plan to be involved in the exchange of resources and indirect partners - the ones that can develop an indirect type of collaboration however necessary to support the exchange of resources within the network.
- **Step 2 – Identification of value flows.** These value flows correspond to the resources exchanged between the stakeholders within a symbiosis relationship and can either correspond to tangible or intangible resources. The value flows are based on the resources on which an organization is dependent. This means that when a stakeholder controls a valuable resource over another stakeholder, a value flow exists, and it is created from the former stakeholder to the latter, as defined by Hein et al. (2017). Each flow is constituted by a two-way relation: the direct and reciprocal flow, representing the inverse relationship.
- **Step 3 – Quantification of value flows.** To understand each stakeholder's power, it is necessary to quantify the value flows where they engage directly and indirectly. This quantification happens through two main criteria defined and adapted by Hein et al. (2017) to the industrial symbiosis context – the "urgency" and the "dependence" criteria, whose scores were developed by Feng (2013) for the stakeholder value network. To Ferreira et al. (2019), the "urgency" score (Table 2-7) defines the urgency for a receiving stakeholder to get a specific resource, considering a "time-sensitivity notion". The "dependence" score (Table 2-8) measures the dependence of a specific stakeholder to supply a specific resource in one particular exchange.
- **Step 4 – Matrix of value flows.** This matrix characterizes the flows exchanged between the stakeholders in an ISN. It allows visualizing the exchanges between the stakeholders and quantifying their desire to be involved in those exchanges. The matrix also identifies which stakeholders hold the most power in the network, thus allowing for understanding the power distribution among the networks' stakeholders. The value flow matrix is generated through the combination of two criteria (Table 2-9) used to quantify each dyadic relation of the network - the "urgency" and "dependence" criteria.

Table 2-7 Urgency score and levels according to Feng et al. (2013, p.160)

Urgency score	Urgency levels
0.11	It can be fulfilled after four years from now
0.22	It should be fulfilled between the third and fourth year from now
0.33	It should be fulfilled between the second and third year from now
0.66	It must be fulfilled next year
0.98	It must be fulfilled this year

Table 2-8 Dependency score and levels according to Feng et al. (2013, p. 161)

Dependence score	Dependence levels
0.11	Not important – I do not need this source to fulfil this need
0.33	Somewhat important – It is acceptable that this source fulfils this need
0.55	Important – It is preferable that this source fulfils this need
0.78	Very important – It is strongly desirable that this source fulfils this need
0.98	Extremely important – It is indispensable that this source fulfils this need

Table 2-9 Combined punctuation for the “urgency” and “dependence” criteria. Retrieved from Feng (2013)

Dependence score	**0.98**	0.11	0.22	0.32	0.65	0.96
	0.78	0.09	0.17	0.26	0.51	0.76
	0.55	0.06	0.12	0.18	0.36	0.54
	0.33	0.04	0.07	0.11	0.22	0.32
	0.11	0.01	0.02	0.04	0.07	0.11
		0.11	**0.22**	**0.33**	**0.66**	**0.98**
		Urgency score				

2.3 Chapter summary

This chapter has reviewed the pertinent literature to explain the industrial symbiosis phenomena in the AM context and highlights the areas that are not yet completely understood or well advanced and, thus, require further research. The background related to ISNs and AM was considered. A systematic literature review on industrial symbiosis and the AM was presented to show that despite the potential of the AM industry to promote the development of ISNs, there is still a lack of research relating to these topics. The concept of additive symbiotic networks was introduced.

Models for analysing ISNs were explored and adapted to the additive symbiotic network setting. The chapter ends with a methodology based on existing models and criteria to assess the power distribution among the symbiotic' stakeholders in a symbiotic network.

3

BLOCKCHAIN TECHNOLOGY AS AN ENABLER OF ADDITIVE SYMBIOTIC NETWORKS

Considering the digital nature of additive symbiotic networks, the inexistence of trust or cooperation mechanisms between the symbiotic stakeholders, and, moreover, the need to find tools to support the exchanges between the stakeholders of a symbiotic network, there is a need to find a suitable technology to support them and that provides a trusted tracking solution (Alkhader et al., 2020). Thus, there is increasing potential for studying blockchain technology within an additive symbiotic network setting. Blockchain technology, as one of the Industry 4.0 technologies, is seen as typical technology which may contribute to companies implement circular economy ecosystems assuring the reliability, traceability and transparency of information (Maranesi & De Giovanni, 2020).

In this chapter, these topics will be further explored and developed. The chapter starts with an introduction to blockchain technology. After, the adoption of this innovative technology in an industrial symbiosis context is explored, precisely the blockchain's requirements that enable the development of additive symbiotic networks. Finally, the implications of adopting blockchain technology within the supply chain of those symbiotic networks are discussed.

3.1 The blockchain technology

Over the last years, blockchain technology has gained substantial awareness and hype as a disruptive technology with several promising benefits, including improved traceability and transparency, cost savings and enhanced sustainability (Kouhizadeh et al., 2021). Blockchain emerged in the cryptocurrency market as a disruptive technology and gained international momentum when it first enabled mistrusting parties to perform transactions without requiring a centralized trusted third party (Nakamoto, 2008). The beginnings of blockchain go back to the paper written by Nakamoto (2008) that first introduced a peer-to-peer version of electronic cash, the Bitcoin, that allowed online payments to be made directly between parties without the need to go through centralized financial intermediaries (Morkunas et al., 2019).

The blockchain is a distributed database that has registered the records and shared ledgers of all digital actions that have been realized and shared among blockchain participants (agents) or parties (Saberi et al., 2019). According to Wang et al. (2021), blockchain is essentially an encoded digital ledger stored on several computers of a private or public network. Golosova & Romanovs (2018) described the blockchain as an incorruptible digital ledger and also referred to it as distributed ledgers where economic transactions can be coded to record more than just financial transactions but also virtually everything that has value. A single transaction involving one or more entities is the basic unit of a blockchain. This could correspond to a transfer of information, or it can correspond to a payment process. A cryptographic hash is used to generate transaction hashes that encrypt the content of these transactions (Treiblmaier, 2018).

A blockchain holds a unique record of the data that is stored in blocks within each participant's node (Nakamoto, 2008). Each node will have the exact copy of the ledger, and consensus algorithms are used to enforce such integrity claims. Each block corresponds to tamper-resistant records and evident digital ledgers that are usually implemented without a central authority and distributed (Yaga et al., 2018). A block can then be seen as the basic data structure that comprises a list of transactions between nodes and two secure hash values: one related to the previous block and the other related to the block itself (see Figure 3-1). With this, two objectives are supported: block integrity and chain integrity. The secure hash of a block will always result in the same value if the block is unchanged. If a single bit of the block is changed, the secure hash value will differ. Because each block data also includes the secure hash of the previous block, changing a single bit in one block will have a forward cascading effect changing all blocks and requiring re-running consensus algorithms per each changed block. Meaning that, a change in a single bit of a block will be too computationally costly to become feasible.

Regarding the type of access for the participants in a blockchain network, there can be two types of blockchain networks (Wüst & Gervais, 2018):

- A **public** or **permissionless** blockchain allows any node to take part in the network, leaving whenever it decides to and being able to view all transactions that occur (Morkunas et al., 2019; Wüst & Gervais, 2018). A consensus algorithm is used to regulate the participants' nodes that can read or write data (Wüst & Gervais, 2018), more specifically, to achieve consensus in most public blockchains, each node within the network must solve a resource-intensive, complex cryptographic problem (designated by proof-of-work) to guarantee that all nodes of the blockchain are synchronized (Morkunas et al., 2019). *Ethereum* is an example of public blockchain technology.

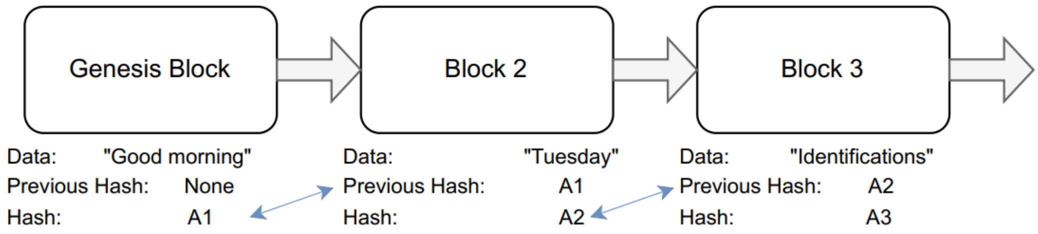


Figure 3-1 Blockchain's Structure. Adapted from: Kasthala (2019)

- A **private** or **permissioned** blockchain has participants' nodes' capabilities differing among themselves, with some being allowed to read and write data to the blockchain, while others are only allowed to read data (Wüst & Gervais, 2018). Morkunas et al. (2019) highlighted that a variant of a private blockchain is the *federated or consortium model*, in which the blockchain operates under the leadership of a group. An example of a private blockchain is a *Linux-based Hyperledger.*

When a group of companies or organizations manages these approved blockchains instead of individuals, it is designated as a consortium blockchain (Shojaei et al., 2021). They are more decentralised than a private blockchain to enjoy more security and lower operation and maintenance costs. It allows limited access, and the current nodes determine the consensus process. A centralised administrator does not need to be involved in defining access control policies since they should be determined by the data owner and applied throughout the entire network (Chen & Bellavitis, 2020). Pre-authorized nodes control the consensus process in a consortium blockchain. The right to read the blockchain can be public or can be limited to specific participants, and several companies can share responsibility for the maintenance of a blockchain. These pre-selected organizations determine who can process transactions or access the data (Liu et al., 2021).

Consortium blockchains are best suited for organizational collaboration. In this manner, a consortium of several companies can agree on a contract text and decide to use a blockchain to save contract manipulation costs (Yuen, 2020). Suppose another company would be interested in admission to the consortium at a later time, the same contractual conditions apply to this company. In that case, the new company could form a hash value (Brousmiche et al., 2018). If this hash value had already been stored in the blockchain, the company could be sure that this contract text was agreed precisely between the other members of the consortium. A blockchain-based credit clearing and settlement process are also faster and more cost-effective through consortium blockchain (Paul & Rakshit, 2022).

Regarding its performance efficiency, security and reliability, usually, performance is higher the more private and closed-off the blockchain is. The reasoning is that simpler consensus algorithms can be used, for instance, based on peer identity. Private or permissioned ones are easier to lower costs, scale up, add reliability and security and possess a higher level of trust, as only pre-verified participants can initiate a new node in the blockchain (Morkunas et al., 2019). On one side, there is a key drawback related to trust versus performance. The participants of a permissioned blockchain must trust the entity behind the blockchain, whereas in a public blockchain, the trust is placed in the network of peers that run consensus algorithms (also known as miners) and in the overall inability to break the system. Despite the differences between public and private blockchains, Morkunas et al. (2019) highlighted that there are common features between them, such as: i) both maintain the replicas synchronized through a protocol – designated as consensus; ii) both guarantee the immutability of the ledger and iii) both are decentralized peer-to-peer networks, in which each participant keeps a replica of a shared attach ledger of digitally signed transactions.

The interactions between the network's nodes ensure that trust is achieved; thus, the blockchain network participants rely on the network itself rather than on trusted third-party organizations to agile transactions (Niranjanamurthy et al., 2019). This advantage is estimated to bring great changes than those brought by traditional technologies. In their study, Makridakis & Christodoulou (2019) briefly described the unique value of blockchain technology, such as follows:

- Immutability and transparency: information can only be attached to previous data; once entered, it cannot be altered or lost, providing an incorruptible historical record of events that is permanent within the systems.
- Disintermediation: the blockchain database is maintained by all the participating computer networks distributed worldwide. This means that two participants can

interact with each other without the need for any intermediary to authenticate their transactions.

- Trust: new information can only be added to the blockchain when most of the network's participants give their approval after receiving proof that the information cryptographically transferred is truthful.
- Substantial improvements: as transactions are possible at any time and without the need of an intermediary, additionally but not always, the blockchain results in considerable cost decrease and greater speed of transactions.

Furthermore, Cole et al. (2019) highlighted that blockchain technology has four critical characteristics that stands-up, namely: i) it is designed to be synchronised and distributed across networks, encouraging companies and businesses to share data; ii) the smart contracts, which are one of blockchain's applications, representing an agreement between entities in the blockchain; they can also define conditions and functions, that may include the validation of assets in a variety of transactions with and without monetary elements; iii) the blockchain is built based on peer-to-peer networks in which there must be an agreement between all the relevant parties for a transaction to be valid, and this helps to keep potentially fraudulent transactions excluded from the database and iv) immutability that means that the transactions that occur within the network are recorded on the database and cannot be altered. In their study, Schmidt & Wagner (2019) emphasized the blockchain's main advantages and challenges Table 3-1.

Blockchain technology assures to increase transparency, responsiveness and speed and, additionality, it can be used for any exchange or work on agreements with no conflicts, as all parties involved have a copy of the ledger and payments are generated automatically (Cole et al., 2019). Besides tracking materials, blockchain technology may be valuable in exchange, facilitating the operationalization of potential regulator entities or even external audits. A blockchain's information is complicated to extinguish or corrupt since blockchains are replicated across a peer-to-peer network (Peck, 2017). Furthermore, Blossey et al. (2019) argued that blockchain networks constitute decentralized autonomous and collaborative organizations for value exchange and creation, allowing to overlap traditional contracts by including the agreements' terms between two or more parties but surpassing them thanks to smart contracts that automate the execution of agreements in a distributed environment when conditions are met (Khan et al., 2021). The following sub-chapter presents the overall functioning of smart contracts.

Table 3-1 Blockchain's main characteristics and challenges. Retrieved from: Schmidt & Wagner (2019)

Advantages	Immutable	Transactions on the blockchain cannot be tampered with once the network validates them.
	Trust	Transactions can be conducted without personal trust between parties, as blockchain provides consensus mechanisms to establish a valid state of truth.
	Transparent	Every participant on the network (in a permissionless setting) can access and view all previous transactions.
	Permanent	Blockchain always holds the entire transaction history. Every transaction that is verified is always retraceable.
Challenges	Data quality	Blockchain is mainly a database whose value depends on input data quality.
	Network effect	Blockchain only creates value for participants, given the sufficient diffusion of the technology.
	Privacy	Blockchain requires every participant to share information within a transaction, even in private configurations.
	Uncertainty	The technological uncertainty is still high, and the technology has not reached a mature state yet.

3.1.1 The smart contracts

Ante (2021) highlighted that while Bitcoin aimed to disintermediate the financial transfer of money, the underlying blockchain technology allowed for some degree of disintermediation in almost any industry or sector and additionally, predefined processes could be decentralised on the blockchain by computer code. This computer coder could prescribe a specific reaction to new information (for example, an incoming transaction). Such scripts are known as smart contracts. Within its several technologies, the blockchain supports the smart contract concept. With the emergence of blockchain technology, other concepts and definitions started to be developed, such as smart contracts. Szabo (1997) defined a smart contract as a computerized transaction protocol that executes the terms of a contract. According to Schmidt & Wagner (2019), this means that the contract is automatically executed when the blockchain achieves a pre-specified state. Since smart contracts are entities within the distributed network, (theoretically) there is no longer a need for a trusted authority to execute the contract. These agreements exist in the blockchain platform as a software code which guarantees their self-executive nature or autonomy based on predefined specifications or rules (Treiblmaier, 2018).

Adopting blockchain technologies allows not only to replace intermediaries with non-value adding but also to aid intermediaries at complex points to improve transparency and promote trust in the service being provided (Durach et al., 2021). The introduction of smart contracts that, when executed, change the state of all nodes that are part of the blockchain enables distributed applications and allows the performance of credible transactions without the involvement of third parties (Saberi et al., 2019). To Ronaghi & Mosakhani (2022), implementing blockchain technology is expected to be effective in business ethics and monitoring corporate governance and to achieve sustainability.

Moreover, in smart contracts, conditions and functions can be defined outside of the exchange of cryptocurrencies, such as the validation of assets in a specific range of transactions that include non-monetary elements, which makes it a very suitable component to expand the blockchain technology to other areas (Reyna et al., 2018). Saberi et al. (2019) explained in a simple way the logic behind smart contracts: once the network of participants has reached a consensus on the outcome of the contract execution, the contract is executed. Whenever the contract receives a message (which may come either from another contract or by a network participant), it executes its code and updates the ledgers accordingly if the contractual terms of its private and public network are met.

Smart contracts brought a set of advantages such as speed, precision, cost reduction, transparency and efficiency that fostered many new applications in a broad range of areas (Reyna et al., 2018) and, according to Upadhyay (2020), smart contracts provide huge potential for removing manual intervention, bias and increase transparency. Furthermore, Paul et al. (2021) highlighted that smart contracts could help to record interactions between the stakeholders involved in the system as written rules are recorded in the blockchain.

Different blockchain technologies comprise smart contracts' functionalities, such as Hyperledger or Ethereum. To Gonçalves et al. (2022), on the one hand, the Hyperledger Fabric is a permissioned blockchain that does not have any cryptocurrency built-in, and on the other hand, Ethereum is a permissionless blockchain that offers a built-in cryptocurrency, having its transactions open and transparent to everyone. Table 3-2 compares both blockchain technologies.

Table 3-2 Comparison between Ethereum and Hyperledger Fabric. Retrieved from Gonçalves et al. (2022)

Characteristics	Ethereum	Hyperledger Fabric
Purpose	Business to contract and generalized applications	Business to business
Access	Permissionless	Permissioned
Consensus	Proof of Work – it requires the use of computer power by miners to validate the new block of the network	Pluggable Consensus algorithm
Native currency	Ether	None
Visibility of transactions	Transparent	Confidential
Programming languages	Solidity, Go	C++, C#, Go, Haskell, Java, JavaScript, Python, Ruby, Rust, Elixir, Erlang

3.2 Boosting additive symbiotic networks using the blockchain technology

According to Rajput & Singh (2019), value networks need to be integrated for transparency to transition from a linear to a circular economy, and sustainability can be achieved through integrating the circular economy and the Industry 4.0. The umbrella of Industry 4.0 technologies (Dalenogare et al., 2018; Vaidya et al., 2018) is expected to boost the implementation of circular economy ecosystems (Maranesi & De Giovanni, 2020). Companies or organizations can use those technologies to analyze large amounts of data in real-time, improve transparency, improve operational and strategic decision-making, and have more flexible manufacturing processes (Dalenogare et al., 2018).

Within circular economy ecosystems, specifically in symbiosis networks, as highlighted in sub-chapter 2.1.1, the economic and social exchanges that occur within an ISN are characterized by value flows between stakeholders, creating a value network. The interrelationships between the different stakeholders create an opportunity to implement circular ecosystems, but they also involve challenges, such as transaction costs, distributed power relations, intermediaries in the system, and interdependencies to capture, create and deliver value (Kanda et al., 2021).

Yeo et al. (2019) emphasized that few information and communication technology tools are available to support the industrial symbiosis process implementation phase, as shown in Table 2-1. Those authors described the *Core Resource for Industrial Symbiosis Practitioners* as a platform to support the industrial symbiosis progress tracking and project management. Furthermore, other tools could be applied, for instance, performance measurement tools that generate metrics to assess the performance of industrial symbiosis exchange. However, such approaches are usually easily used in either single organizations or single supply chain systems, and even though the principles can be applied to different organizations in cross-industry networks (as the ISNs), those efforts are often impeded due to confidentially issues, data gaps, and discrepancies (Tseng et al., 2018). Therefore, there is a need to find tools that contribute to developing such symbiotic exchanges between different industries, enhancing the development of ISNs.

Moreover, the successful adoption of AM technologies introduces challenges due to their digital nature, such as a verifiable source of production, quality issues, intellectual property questions, adherence to standards and copyright protection (Alkhader et al., 2020). When considering the context of distributed networks, such as the ones comprising multiple AM services providers and original equipment manufacturers, there is a need to build trustful relationships among the different participants or to develop security approaches to establish a chain of trust among them (Kurpjuweit et al., 2019). To Albino et al. (2016), a trusted environment is widespread in industrial networks, allowing for sustaining and nurturing cooperative exchanges. Furthermore, trust is also highlighted as one of the most prominent challenges within the literature around symbiosis networks (Madsen et al., 2015; Ponis, 2021). Trust is highlighted by Albino et al. (2016) as being favoured by geographical proximity among firms and the existence of strong social ties, familiarity, and shared norms among firms that enhance the transparency of actions and information sharing and fosters cooperation between firms. In the additive symbiotic network, similar challenges emerge: the need to trace AM resources used (including digital files, input materials, and AM technologies), the need to exchange sensitive information between symbiosis partners who do not have developed any relationship so far and thus, the need to develop trustworthy relationships. In this sense, there is a need to find tools that support not only the digital process chain (Kurpjuweit et al., 2019) associated with the networks but that also provide a trusted tracking solution (Alkhader et al., 2020), such as blockchain technology and hence, contributing to the development of the symbiotic exchanges, enhancing ISNs.

Blockchain technology can be a tool not only to deal with the challenge related to trust (Ponis, 2021) among the different stakeholders but also to provide the necessary technical support for the transactions occurring in the network. It can be used to securely store information like the stakeholders' data, the process characterization, energy consumption, and trace products and materials (Kouhizadeh et al., 2020; Wang et al., 2021). Smart contracts can be used to assure that waste across the value chain is minimized, for example, by including performance criteria for suppliers for waste reduction metrics. Suppose it is assumed that there is no possibility of reducing waste in the value chain. In that case, smart contracts enable other opportunities that might contribute to waste reduction, such as identifying where and how the wastes can be used to minimize their environmental impact within that supply chain (Kouhizadeh & Sarkis, 2018).

Moreover, Gonçalves et al. (2022) suggested that industrial symbiosis could benefit from adopting blockchain technology and related concepts, such as smart contracts or cryptocurrencies. The access to the information given by blockchain technology allows stakeholders to validate and exchange information about demand, specifications, supply and prices, among others (Chidepatil et al., 2020). Additionally, Ponis (2021) evidenced that the potential of blockchain technology to support environmental sustainability was related to the capability to provide a verifiable record of who and what is exchanged and, consequently, what every actor has at a given time. This technology can serve as a distributed platform for trading by-products and materials, connect companies, and motivate the exchange of wastes without intermediaries, improving profit margins (Kouhizadeh et al., 2019).

In this sense, a consortium blockchain is ideal in an industrial symbiosis setting or if all participants must have approval and have a joint responsibility for the blockchain. By using the consortium blockchain in ISNs, it is possible to track the source of raw materials, wastes and by-products, the amount of energy used during production, the type of energy consumed throughout their life cycle, and the impact of the energy on the environment and resources (Shojaei et al., 2021).

For instance, considering the smart contract architecture to enhance an industrial symbiosis network within the pulp and paper industry, developed by Gonçalves et al. (2022), Figure 3-2 contains a visual representation of a smart contract formalised between an industrial unit participant and two companies. This is just one type of industrial symbiosis configuration, and the model can be applied to several other types of configurations as well.

In the case described by Gonçalves et al. (2022), the industrial unit participant (which is a Pulp and Paper plant) can, through a smart contract, create an order to sell waste or by-products - this influences the blockchain, causing it to verify and analyze the request. A new block is added to the chain with this further information if it is valid and accepted. From there, Sand Producers' Companies and Mortar Producers' Companies have the opportunity to list the newly added sell order data through a query request or buy waste or by-products through an invoke request. With the second one, once again, the blockchain will be influenced, resulting in a new block being created if all checks are valid with the purchase transaction data. A Certification Authority validates the agreement in the smart contract and reaches the Pulp and Paper plant that agrees to sell an amount of waste or by-products.

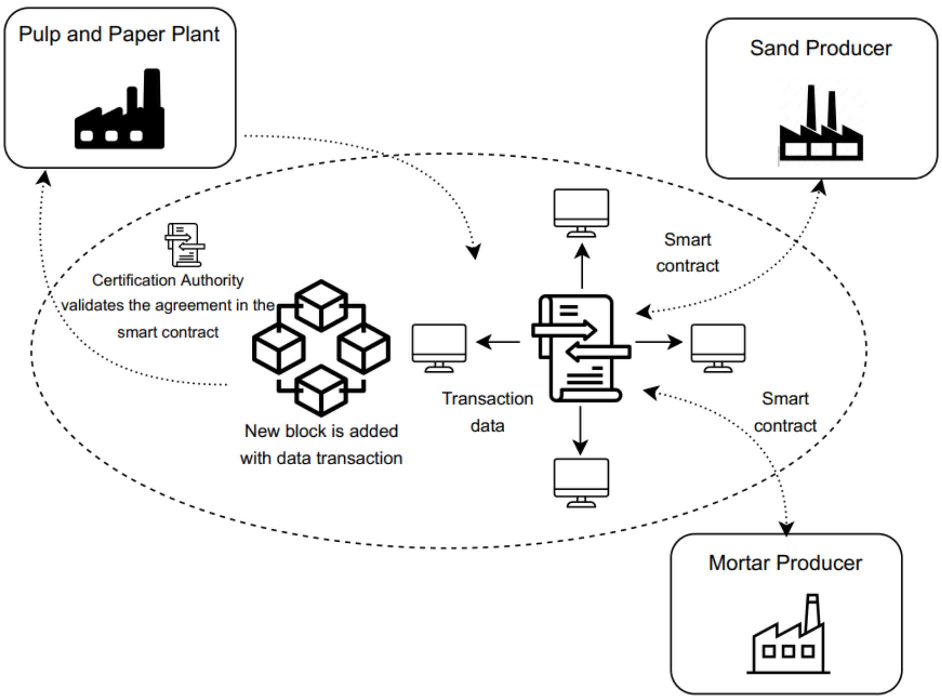


Figure 3-2 Exemplification of a smart contract formalisation in an ISN

Adopting blockchain technology from a technological standpoint has been addressed multiple times (Ganeriwalla et al., 2018; Koens & Poll, 2018; Peck, 2017; Wüst & Gervais, 2018). Despite the already existing body of knowledge, blockchain technology is still in its early development when applied in ISNs settings, with multiple entities and companies exchanging resources (Gonçalves et al., 2022).

3.2.1 Blockchain's requirements to enable additive symbiotic networks

When studying the relationship between AM technology and circular ecosystems, transparency plays a vital role in the production processes, materials used, and disclosure of material sources (Despeisse et al., 2017). Additionally, trust was already highlighted as one of the most prominent challenges within the literature around symbiosis networks (Ponis, 2021). Thus, for an additive symbiotic network to be effectively implemented, it becomes critical to integrate advanced and global technologies that can provide real-time information and can further be used for cognitive or predictive analysis (Rajput & Singh, 2020), such as blockchain technology. According to Kouhizadeh et al. (2020), blockchain technology and its capabilities support the circular economy implementation and development at various levels, such as reliability, information transparency and automation that may leverage circular economy initiatives.

There are several potential benefits in adopting blockchain technology for promoting the development of the industrial symbiosis concept. With the adoption of blockchain technology, companies can ensure a secure and transparent process of transactions (Khan et al., 2022) and furthermore, the blockchain technology features' have been claimed by scholars to have huge potential in facilitating transformation within multiple industries and disrupting transaction approaches (Ning & Yuan, 2021). Blockchain technology can provide the necessary infrastructure not only for companies but also for clients to conduct online transactions without the typical need for an intermediary entity (commonly used to guarantee security) and consequently reduce the costs associated with transactions (Durach et al., 2021). Within the scope of this PhD research work and considering additive symbiotic networks, it is expected that the benefits and challenges brought by blockchain technology to enhance ISNs are extended in the context of additive symbiotic networks.

Few works have been developed relating blockchain technology to the AM industry (Kurpjuweit et al., 2019). Recent works have only focused on copyright and intellectual property protection or as an anti-counterfeiting mechanism (Holland et al., 2017; Kennedy et al., 2017; Kurpjuweit et al., 2019; Mandolla et al., 2019). Even though all the potential benefits, adopting new and disruptive technologies such as the blockchain and AM technologies should be carefully evaluated depending on a company's business goals and sector (Gatteschi et al., 2018). The adoption of a blockchain should consider the requirements of those additive circular ecosystems; this subject remains unexplored in the literature.

At first sight, blockchain can potentially be used in a large spectrum of situations (Atzori, 2017). However, Peck (2017) stresses the need to justify the use of blockchain and choose the adequate type of blockchain considering the needs of a company or service. For instance, Sivula et al. (2021) explored the adoption of blockchain technology using three companies within the construction industry. Kayikci et al. (2022), on the other hand, examined the critical success factors for implementing blockchain-based circular supply chains. Additionally, Sadeghi et al. (2022) evaluated the requirements for implementing blockchain technology in construction supply chains, prioritizing them based on circular economy attributes.

As highlighted at the beginning of this sub-chapter, additive symbiotic networks can benefit from using the blockchain differently. In this PhD research work, the work from Sivula et al. (2021) was extended to the additive symbiotic networks context. Table 3-3 presents how the additive symbiotic network contexts and their stakeholders can use blockchain technology.

Despite several attempts made by scholars and industrial sectors to apply blockchain technology for business process improvement, adopting this new and disruptive technology is still in an earlier stage (Xu & Viriyasitavat, 2019).

According to Sadeghi et al. (2022), several requirements must be considered before adopting and implementing blockchain technology. Authors as Hastig & Sodhi (2020) have identified business requirements and factors critical to a successful implementation of blockchain. Other authors, such as Sadeghi et al. (2022), concluded about requirements at the industry level (specifically related to the industry under study and also regulatory or legal requirements), requirements at the inter-firm level (these requirements exist when organizations interact with each other or engage in a decentralized ecosystem) and requirements at the organization level (that are related to the organizations and firms as individuals actors). Others, such as Irannezhad (2020), have explored technical (related to the platform) performance requirements of adopting blockchain in Port Community Systems.

Considering the additive symbiotic network context and the different stakeholders involved, a focus on inter-firm level requirements is given in this PhD research work. Hence, reckoning the existing lack of research regarding the use of blockchain technology in an additive symbiotic network setting, the decision diagram developed by Peck (2017) (Figure 3-3) was further taken into consideration.

Table 3-3 Use of blockchain technology in the additive symbiotic network context

Stakeholders in an additive symbiotic network context	Blockchain's technology utilization
Manufacturing company	Blockchain technology can be adopted on one hand to make available information about potential stakeholders and wastes or by-products value streams. On the other hand, the technology can also streamline the stakeholders' transactions through smart contracts.
AM technology provider	These stakeholders in the additive symbiotic network can use the data which is part of the blockchain for ordering the products from the companies using additive technologies. Additionally, blockchain allows the management of separate agreements and contracts between the stakeholders in the network.
Intermediary	Intermediary stakeholders can be connected to services' providers, such as financial consulting services that include search for funds or legal consulting services. Blockchain technology can directly process the transactions between the stakeholders without the need for a typical intermediary or help necessary intermediaries to solve complex problems.
Retailers and other product sellers	Receiving the data concerning the final AM goods or materials made from the waste streams. Management of different customers and contracts.
Prosumers and Customers	Using the data available in blockchain that relates to AM products purchased.

The following requirements are highlighted:

- **A traditional database does not meet the additive symbiotic networks' needs.** Traditional and conventional core logic databases (such as Microsoft SQL Server, Oracle Database or MySQL), used by each stakeholder in an additive symbiotic network, would need to have a specific function for the exchange process. After this, all the databases should be connected with each other. Furthermore, when considering the AM industry, there may be a need to track the quality of the additive materials inputs during the exchanges - which a traditional database does not allow.

- **More than one participant needs to update the data in the database.** When considering additive symbiotic networks, there is a need to keep available some critical information for the resources exchanged. These can include: i) the main AM technology or process used to transform the waste materials into value-added products, ii) information regarding the percentage of waste material used, iii) quantity produced from the value-added products, and iv) quality of those products. Considering that this information is made available by different stakeholders in the network, at least two of those stakeholders (for example, the manufacturing company or the company that distributes the additive technology) need to change and update the status of the transactions.

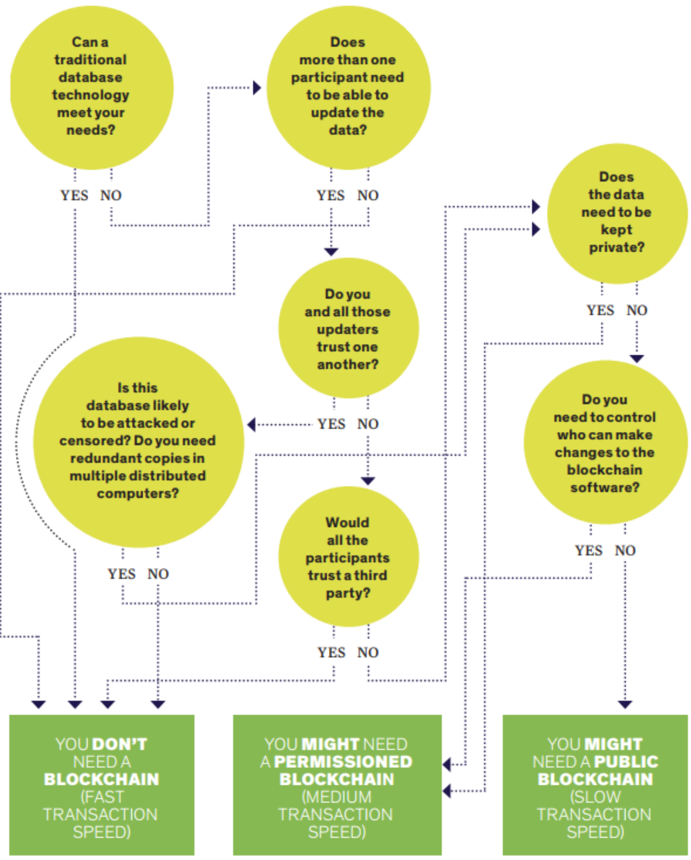


Figure 3-3 Can blockchain technology solve a company's or service's problem? Retrieved from Peck (2017)

- **No trust mechanisms exist between the additive symbiotic stakeholders.** New relationships are being created between stakeholders in an additive symbiotic network, likely as in an ISN. These stakeholders might be geographically separated and do not know each other. In the case of the AM industry and since AM is still emerging in the context of circular economy ecosystems, no mechanisms of trust or cooperation have been established yet with other industries.

- **The additive symbiotic stakeholders do not trust a third party.** Considering the previous requirements and the fact that in an additive symbiotic network, no trust exists between the stakeholders involved, it is expected that they do not also trust a third party.
- **Data may or not be needed to be kept private.** In additive symbiotic networks, data is not required to be held in private. In fact, in these additive symbiotic networks, the stakeholders involved should be allowed to monitor each transaction's status.
- **There might be a need to control who can make changes in the database.** In an additive symbiotic network, similarly to other ISNs, there is a power distribution among the stakeholders involved, meaning that there are stakeholders who hold more power within the network compared to others. Thus, trust imbalances may arise, and consequently, in specific additive symbiotic networks, the focal organization may be responsible for creating and maintaining the network.

Even though the potential of the blockchain to enable additive symbiotic networks, adopting such innovative and disruptive technology may lead to some changes in the supply chain of those networks. The following sub-chapter 3.2.2 focuses on understanding the implications of adopting blockchain technology in the supply chain of an additive symbiotic network.

3.2.2 Implications of adopting the blockchain technology in the supply chain of an additive symbiotic network

Even though all the potential benefits of adopting blockchain technology within an industrial symbiosis setting, as shown in the previous sub-chapter 3.2.1 adopting such technology may impact the supply chain of the symbiotic networks. Ellram & Cooper (2013) also make the case for the idea that the Mentzer et al. (2001, p. 3) definition of 'supply chain' is now well-established. That definition is: "*a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer (and return)*". Inside this broad definition is a range of models for studying and analysing supply chains. According to Herczeg et al. (2018), operational aspects of industrial symbiosis relationships involve the management of material and informational exchanges and, furthermore, can connect different levels of actors, leading to a chain of suppliers and buyers, allowing organizations to participate in more material exchanges at the same time.

Blockchain technology can be seen as a new information and computing flow paradigm that may influence the future development of logistics and supply chain management (Saberi et al., 2019). Information sharing connects dispersed entities, which facilitates improving relationships within supply chains, reduces risks and costs, and prevents falsification and fraud (Kouhizadeh et al., 2019). Furthermore, Khan et al. (2022) highlighted that with the adoption of blockchain technology, companies could improve efficiency and reduce overall costs through regenerating resources. In the supply chain management field, the specific applications of blockchain technology include contract enforcement, record keeping and transaction functions (Ning & Yuan, 2021). The supply chain management involves designing, planning, executing and monitoring logistics processes. Lagorio et al. (2020) highlighted in their systematic literature review those innovative technologies, such as the blockchain, can support that distinct variety of activities.

Cole et al. (2019) reveal several opportunities to study blockchain technology within the supply chain management field. In Table 3-4 these opportunities were extended to the supply chain of an additive symbiotic network.

The development of additive symbiotic networks involves several independent companies or organizations that exchange material, services, monetary, informational and knowledge flows, and thus, according to Karuppiah et al. (2021), this is manifested through a supply chain in which those flows occur between different entities. As demonstrated by Gonçalves et al. (2022) and Ponis (2021), blockchain technology can be used to enhance the development of additive symbiotic networks. One of the blockchain applications is smart contracts that can potentially decrease the impact of bounded rationality within a transaction. Bounded rationality is emphasized by Momo & Behr (2021) as a human condition that relates to limitations in the cognitive domain and, when considered within a transaction context between different organizations, does not allow to predict all types of situations that can affect the contract among the organizations. However, by creating a more reliable transaction, Cole et al. (2019) highlighted that blockchain technology can significantly reduce the need for an intermediary entity, removing the middleman and creating an even more transparent and agile supply chain.

Additionally, blockchain technology offers an immutable and permanent database where information is shared efficiently, without the need for a long-term relationship (Schmidt & Wagner, 2019).

Table 3-4 Potential use of blockchain technology in the supply chain management field.

Potential uses of blockchain technology in the supply chain [(a)]	Description [(a)]	Additive symbiotic network context
To improve and automate contracts	Blockchain is an emerging technology that is based on transactional and decentralized data sharing across a network that does not need trusted participants. The complexity of manufacturing ecosystems requires the development of new ways of trust through blockchain technology and smart contracts.	With blockchain and smart contracts, trust in enhanced among the stakeholders in an additive symbiotic network and reduce the need to develop a long-term relationship between the stakeholders, reducing dependency and increasing transparency between them.
To reduce the need to develop trustworthy supply chain relationships		
To reduce the need for intermediaries and consequently reduce the supply chain's complexity	With smart contracts performing their role reliably, international procurement organizations will no longer be needed.	Through the use of smart contracts within an additive symbiotic network, there is no longer a need for intermediary entities as the smart contracts are directly performed between the buyer and the seller (reducing the dependency on a third party), thus, creating a more transparent and agile supply chain.
To reduce the costs of transactions through automation, enabling real-time auditing via timestamping	The costs of many transactions have been lowered with digitisation. The blockchain technology introduction supports digitisation through costless verification.	By reducing the costs for verification and validation of transactions, blockchain technology reduces overall transaction costs in an additive symbiotic network.
To enhance product safety and security	Through the application of blockchain and smart contracts that provide records of testing, the security of the whole supply chain can be enhanced.	Blockchain and smart contracts provide real and trustful records about each network transaction, improving the supply chain's security and transparency.
To enhance quality management by providing accessible information about batches	Paper-based freight documents are tampering and prone to loss and fraud. The blockchain can provide visible and easily accessible information about batches, improving service and aiding recalls.	Blockchain technology can provide easy and accessible information about the resources exchanged between the stakeholders of an additive symbiotic network.

Table 3-4 Potential use of blockchain technology within the supply chain management field. (cont.)

To reduce illegal counterfeiting	Blockchain technology can provide information about the origin of a product, strengthening the transparency and traceability of goods in a supply network.	Blockchain technology improves transparency and traceability of the goods exchanged within the network and, thus, helps to mitigate risks related to the intellectual property of AM files.
Improve inventory management	With the use of smart contracts, inventory management challenges can be overcome.	Through the use of smart contracts in an additive symbiotic network, it is possible to control what resources (wastes, by-products and products) each stakeholder holds at each point in time.
To accelerate work on the design and new product development	Blockchain technology has allowed the development of new insurance products, improving efficiency and delivering greater transparency between teams.	Blockchain technology improves efficiency and transparency between organizational teams of each stakeholder involved in the supply chain of an additive symbiotic network. It also enhances the transparency of the digital data files of the products produced through AM.
To revolutionise the Internet-of-Things in Operations Management	Blockchains provide the basis for an open manufacturing system that shares data with its customers and knowledge on handling the data that is shared with other organizations involved in the supply chain.	Blockchain technology provides a database that allows data sharing between the stakeholders involved in the supply chain of an additive symbiotic network but simultaneously controls who can access these specific data.
Note: [a] - retrieved from Cole et al. (2019)		

The additive symbiotic networks require supply chains to expand their traditional relationships to a more collaborative effort (Herczeg, 2016). In these networks, inter-organizational relationships are established through synergistic transactions that include different sellers and buyers with geographically distant customer locations (Karuppiah et al., 2021). Improvements, especially in digital technologies, impact supply chain management and logistics (Jamkhaneh et al., 2022). According to Treiblmaier (2018), with the adoption of blockchain technology, the direct relationships within a network are still maintained, but their strength might be affected, and also, indirect relationships might be replaced by new direct ones. Thus, it is expected that adopting blockchain technology in an additive symbiotic network has implications for the structure of its intrinsic supply chain (Durach et al., 2021; Oh et al., 2022; Treiblmaier, 2018).

There are three main dimensions of the supply chain structure with an essential impact on addressing social and economic issues (Awaysheh & Klassen, 2010):

- Dependency - the degree to which organizations rely on other supply chain members for critical resources, capabilities and components.
- Distance - encompasses three sub-dimensions: geographical distance (relates to geographical separation), cultural distance (reflects the existing differences between the cultures of the societies in which organizations are based) and organizational distance (defined by the number of tiers that exist between the focal firm and suppliers or customers, and the length of the supply chain).
- Transparency - captures the extent to which information is readily accessible to organizations and end-users in the supply chain.

Four theories within the supply chain management field can be used to explore the implications in the supply chain of a network with the adoption of the blockchain technology: transaction cost analysis (Halldorsson, 2002), the resource-based view (Miller & Ross, 2003), network theory (Gadde & Hakansson, 2001) and the principal-agent theory (Logan, 2000). According to Treiblmaier (2018), the transaction cost analysis and the principal-agent theory are used to answer questions regarding how to structure or design a supply chain; and the network theory and the resource-based view help answer questions regarding what is needed for managing those supply chain structures.

Furthermore, considering one of the objectives of this PhD research work that concerns with understanding the implications of adopting the blockchain technology in the supply chain structure of additive symbiotic networks, there is a need to understand the management of the relationships between the organizations involved in the networks (Boons & Baas, 1997). In this sense, the network theory is linked to dyadic relationships embedded in networks (Halldorsson et al., 2007) and, according to Treiblmaier (2018), evaluates connections and exchanges between organizations, focusing on managing relations rather than the transactions themselves. Its main objective is to explore the role and nature of inter-organizational relationships and how they can be managed. Thus, the network theory was considered to be a suitable lens to understand the implications of adopting blockchain technology in the supply chain structure of an additive symbiotic network. When applied to the supply chain management field, the network theory has been used to map actors, resources and activities in the supply chain (Halldorsson et al., 2007). Treiblmaier (2018) highlighted in his study how the different attributes of blockchain technology could be incorporated within the network theory (Table 3-5).

Table 3-5 Blockchain-based supply chain management research. Retrieve from Treiblmaier (2018)

Characteristics of the Network Theory	Blockchain-based networks
Behavioural assumptions	Interorganizational trust, information sharing
Problem orientation	Design of transactions and communication
Key questions	To what extent does the blockchain replace personal trust?
Primary focus of analysis	Relationships within the network
Nature of relations	Contractual relations, personal relations
Primary domain of interest	Mutual adaption of relations through the blockchain technology

Oh et al. (2022) emphasized that research employing qualitative methods is needed to explore the meaning of blockchain technology in the supply chain management domain and in designing processes of blockchain-technology-enabled supply chains. Furthermore, Kummer et al. (2020), in their systematic review of blockchain literature and the supply chain management, highlighted that several studies are already examining the adoption of blockchain technology using the network theory. However, the literature regarding the implications of adopting blockchain technology in the supply chain structure of additive symbiotic networks remains to be further explored. Thus, the literature presented above suggests a need to use a network theory lens to understand the implications of blockchain technology in the supply chain structure of an additive symbiotic network. These implications are expected to be associated with the relationships within the network, specifically with the strength of their ties and embedded with other relationships (Queiroz & Fosso Wamba, 2019).

In this PhD research work, the definition of a conceptual model from Meredith (1993) was considered: a conceptual model is a set of concepts, including or not propositions, used to describe or represent (but not explain) an object, process or event. This study focuses on additive symbiotic networks in which wastes or by-products from several industries are used in AM processes as material inputs. As previously highlighted in sub-chapter 1.1, wastes are objects or substances intended or required to be discarded, and by-products are production residues that satisfy the four conditions settled by the WFD to be considered as by-products.

Different stakeholders constitute additive symbiotic networks (for example, companies from distinct industrial sectors or services companies, local entities, governmental/municipal offices, non-governmental organizations, research centres, consumers, suppliers, and others) exchanging resources between them, such as material, services, monetary, and information and knowledge. This involves the management of material, monetary and informational and knowledge exchanges in a supply chain setting.

A conceptual model for understanding the implications of adopting blockchain technology in the supply chain structure of an additive symbiotic network is proposed (Figure 3-4). Using a network theory lens, the primary focus of analysis is the relationships within the intrinsic supply chain of the additive symbiotic network (Treiblmaier, 2018). This conceptual model considers that the relationships between the stakeholders in an additive symbiotic network are used as a proxy to assess the supply chain structure. These relationships may be characterized through the methodology based on the Stakeholder Theory, presented in sub-chapter 2.2.

Additionally, the conceptual model comprises four supply chain management areas, previously identified by Cole et al. (2019) and extended to the additive symbiotic networks context (Table 3-4), that relate to the supply chain structure, where blockchain technology is considered to bring value by: i) improving and automating contracts, ii) reduce the need to develop trustworthy supply chain relationships, iii) reduce the need for intermediaries and consequently reducing the complexity of the supply chain, and iv) reduce the transactions cost through automation.

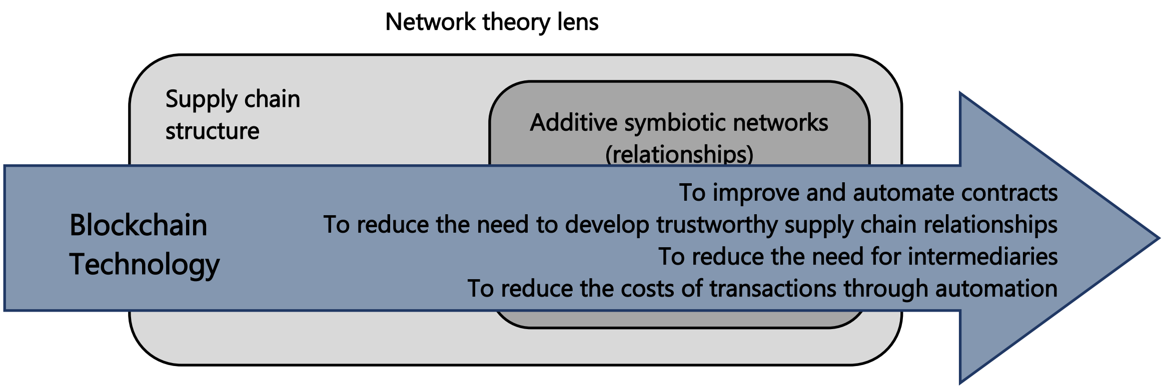


Figure 3-4 Conceptual model to understand the implications of adopting the blockchain technology

3.3 Chapter summary

Chapter 3 highlighted the potential of adopting blockchain technology as an enabler for additive circular ecosystems, specifically for developing additive symbiotic networks. An overview of blockchain technology and smart contracts is provided. Despite the evident potential of adopting such a disruptive technology as blockchain technology in an additive symbiotic network setting, there is a need to understand if the technology may be adopted in such settings. A decision diagram is presented to help find out if and how blockchain technology can or cannot be applied to additive symbiotic networks.

Considering the decision to adopt the blockchain in an additive symbiotic network, this chapter highlighted several implications within the supply chain structure of the symbiotic network. These are: to improve and automate contracts, to reduce the need to develop trustworthy supply chain relationships, to reduce the need for intermediaries and consequently to reduce the complexity of the supply chain, and finally, to reduce the transactions cost through automation. This chapter ends with the proposal of a conceptual model to understand the implications of adopting blockchain technology in the supply chain structure of an additive symbiotic network, considering a network theory lens.

4

Research Methodology

State-of-art on ISNs, additive symbiotic networks, the adoption of blockchain technology, and its consequent implications on the supply chain structure of an additive symbiotic network were presented in the past chapters. However, to carry on the study, a research methodology is needed. This chapter explains, in a first instance, the researcher's ontology and epistemology. After, the research process is presented, following the justification for using a qualitative research approach, precisely the case study method. The case study selection is justified, and after a discussion is made around the data collection and analysis procedures used in this PhD research work. The criteria to assure the case study quality are also presented, as well as a discussion of the main limitations of using the case study approach.

4.1 Ontology and epistemology

If, on the one hand, according to Karlsson (2016), ontology refers to the researchers' assumptions about the essence of the phenomena under investigation, in which the main question is whether reality is socially constructed. On the other hand, epistemology has to deal with the researchers' assumptions on the status and nature of knowledge and how one might understand the world and communicate its understanding as knowledge to others (Karlsson, 2016). In management and operations studies, two main distinct philosophical foundations prevail: the positivist and the alternative approaches (which include interpretivist and critical realistic alternatives). Both have a significant effect on how the research approach is practised. While the former sees reality as objective, the goal is to discover an objective truth and provide results and conclusions that may be verifiable, generalizable and replicable. The latter assumes that reality is socially constructed, and the researchers' task is to produce detailed descriptions of a particular situation to understand how reality is constructed.

This research adopted a positivistic paradigm where the researcher sees reality as external to the observer. This can be understood throughout the research, where observable facts are emphasised. Two main authors are highlighted in management studies following a positivist paradigm based on this research work: Eisenhardt (1989) and Yin (1994). According to Piekkari et al. (2009), in management research, Eisenhardt prefers to use case studies for theory building, whereas Yin focuses on more practical concerns for applications to consulting and policy making. This PhD research uses the case study methodology, taking a positivistic approach. The main motivations that justified the selection of this methodological approach are further highlighted in sub-chapter 4.2.

There are four main points of difference when considering positivistic or alternative approaches (Piekkari et al., 2009): theorizing with case study, case selection, data sources and boundary setting. These points are now discussed within the scope of this research work.

Ragin & Becker (1992) differentiate between two positions concerning how case studies may be used for theorizing: variable and case-oriented. The first one seeks to arrive at a general causal law that can predict relationships regardless of the context. The latter represents a contrast to the variable-oriented assumptions, producing holistic and specific explanations for the outputs of the case under investigation (Piekkari et al., 2009). This PhD research work adopts a positivist goal of theory towards a variable-oriented explanation, even though its primary purpose is not to generalize across different contexts.

Regarding case selection, Piekkari et al. (2009) highlighted that there are concerns between seeking new theoretical insights that are derived from the richness of using a single case and a "replication logic" towards multiple cases. For this PhD research work, and following Eisenhardt (1989) and Yin (1994), who both expressed a preference for the use of multiple case studies due to their strengths in providing new insights into a relatively recent phenomenon, two case studies were considered – following a logic "à la Yin".

Regarding the data sources, in both positivist and alternative approaches to the case methodology, most researchers agree that one of the major strengths of adopting this approach is linked to its capability to integrate a variety of data collection methods and procedures (Creswell, 2003). In this PhD research work, multiple data sources were used for conducting the case studies, following Yin (2009)'s perspective that combining different sources is the development of converging lines of inquiry, allowing the triangulation and improving the construct validity of the study (Piekkari et al., 2009).

The last point of difference between the philosophical assumptions has to deal with the boundary setting. Yin (2009) emphasised that design logic is crucial to the case study methodology. Following a positivistic tradition favouring a design logic, Yin's (2009) case study design was followed in this research work.

4.2 Research methodology

4.2.1 Case study research

A case study is a research method that examines, through multiple data sources, a phenomenon in its naturalistic context, which aims at "confronting" theory with the empirical world (Piekkari et al., 2009). The case study explores what is most characteristic and essential in the investigation, thus contributing to a better understanding of the global situation being analyzed (Voss et al., 2002).

Considering the proposed research questions that this PhD research work intends to answer (**RQ1** – *How to promote ISNs in the AM context?;* **RQ2** – *What are the requirements to make use of blockchain technology in an additive symbiotic network?*, and **RQ3** - *What are the implications of blockchain technology adoption in the supply chain structure of an additive symbiotic network?*) the case study method was selected as the research method for the following reasons:

- The case study method enables the researcher to develop insights into a complex and quite unexplored phenomenon (Rowley, 2002; Yin, 2002).
- The method is considered adequate when there is no control over behavioural events or when the boundaries of a phenomenon are unclear (Rowley, 2002).

- The case method is considered to be pertinent in early and exploratory investigations where the variable are still unknown, and the phenomenon is not entirely understood (Voss et al., 2002)
- It is accepted that "*why"* and "*how*" research questions can be effectively approached through the use of a case study method (Rowley, 2002; Voss et al., 2002).

Additionally, according to Karlsson (2016), different types and levels of knowledge are expressed through the maturity of knowledge on a particular phenomenon. He highlighted three types of maturity levels for knowledge: nascent theory, intermediate theory and mature theory. The nascent theory often suggests new connections occurring in a phenomenon with little or inexistent previous theory. The middle point is the intermediate theory which presents provisional explanations of phenomena. Lastly, the mature theory presents well-developed constructs, frameworks or models that had already been studied but are now improved. In this PhD research work and as shown in the literature review chapters (Chapters 2 and 3), the topics under study are in their early beginnings of study in the research community. For instance, there are already developed theories and methodologies from the literature that can be adapted and used in other contexts. For example, the social exchange theory is the basis for the stakeholder value network that consequently allowed the development of the methodology for characterizing an ISNs. Within this PhD research work's scope, this methodology was used to map and characterize additive symbiotic networks.

Another example is the network theory from the supply chain management field that in this PhD research work is applied to explore the potential implications of adopting blockchain technology in the supply chain structure of an additive symbiotic network context. However, the combination of all these topics – the additive symbiotic networks and the use of disruptive technologies such as blockchain technology in these settings has its debate in the literature initiated with this research work. Therefore, this research work positions itself in the nascent theory regarding the maturity of the existing knowledge.

Considering that different research approaches tend to be used at different levels of maturity of knowledge (as Figure 4-1 suggests) (Karlsson, 2016), and since this PhD research work is focusing on a nascent theory regarding the mature existing knowledge on the topics under study, the case study was considered to be the suitable approach.

According to Voss et al. (2002), case studies can be used for several research purposes such as exploration, theory building, theory extension/refinement or theory testing. Considering the current maturity of existing knowledge on the topics under study, this PhD research work is exploratory in its nature. The aim is not to generalize for all contexts nor to define any hypotheses or constructs to be measured. Instead, the objective is to provide new insights into a relatively new phenomenon. Through exploratory studies, relevant and potentially counterintuitive phenomena are observed and identified, which cannot be fully explained by existing theories (Karlsson, 2016). Thus, exploratory case studies are carried out within this PhD research work.

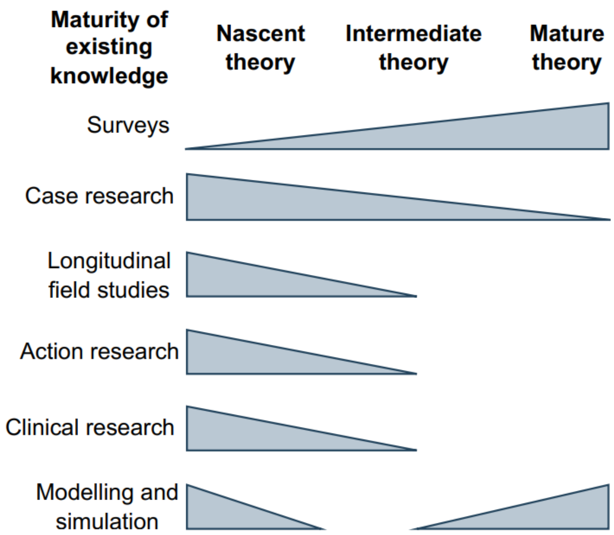


Figure 4-1 Relationships between different levels of existing knowledge and different research methods. Retrieved from Karlsson (2016)

4.2.2 Abductive case study approach

Two main research approaches are distinguished among scholars and researchers: the inductive and the deductive. Caniato et al. (2018) highlighted that case studies are mainly used to build theory inductively. However, those authors also emphasized that sometimes case studies are used for conceptual theory-building, in which the researcher applies a deductive logic to develop the relations between variables and constructs.

In inductive approaches, the central notion is to use the case study as the basis for developing theory inductively (Eisenhardt & Graebner, 2007). The theory emerges in the sense that is developed through recognising patterns of relationships among the different variables or constructs and their underlying logical arguments. Data is collected mostly with qualitative methods, and it is analyzed to achieve an understating of a phenomenon and establish different views of it (Håkansson, 2013).

On the other hand, the deductive approach involves moving from the general to the particular. It starts from a theory, derives hypotheses or propositions from it intending to test those hypotheses or propositions in an empirical setting and finally revises the theory (Woiceshyn & Daellenbach, 2018). The tests are conducted mainly with quantitative methods with large data sets, and, according to Håkansson (2013), the outcome is a generalization that must be based on the collected data and the explanations between variables.

Additionally, there is another approach to acquiring knowledge using case studies – the abductive approach. The abductive approach stems from the insight that most advances in science neither follow the pattern of pure induction nor pure deduction (Kovács & Spens, 2005). However, some authors argue that for findings from the abductive approach to be considered credible and valid, they must be supported by inductively and deductively sourced evidence. The abductive approach follows a different process when compared to the inductive or deductive approaches. It starts with real-life observation, and a creative, iterative process of "systematic combining" or "theory matching" is developed to find a new matching framework or to extend the theory used before the observations. The abductive approach closes with the application of the propositions or hypothesis in an empirical setting (Kovács & Spens, 2005) (Figure 4-2).

Even though, as mentioned in the previous sub-chapter 4.1, a positivistic philosophical assumption is taken in this PhD research work, this should be revealed through an inductive or deductive approach. However, as demonstrated in previous chapters, the literature is scarce on methodologies and tools that can support the implementation and development of additive symbiotic networks. Additionally, the use of disruptive technologies and their implications in the supply chain of those kinds of networks remains to further explored. There is a need to adapt methodologies and models from the existing literature that can contribute to characterizing additive symbiotic networks.

Furthermore, there is a need to understand if innovative technologies such as blockchain technology may be an enabler of these kinds of networks and to what extent it can be used in this context. Since this is an exploratory research, the case studies are being carried out under topics with a low degree of maturity of existing knowledge. Thus, the abductive approach was considered to be the most suitable. Abduction is used to identify the principal methodologies in the literature that could be applied to characterize additive symbiotic networks and to understand the implications in the supply chain structure of those networks with the adoption of blockchain technology. The utility of the abductive approach can be streamlined to aspects such as (Awuzie & McDermott, 2017): the centrality of a researcher's observation concerning a specific phenomenon; reliance on a credible background theory to attempt to explain variables, relationships or hypotheses or propositions; use of inductively and deductively sourced data for validating the explanation of the initial proposition.

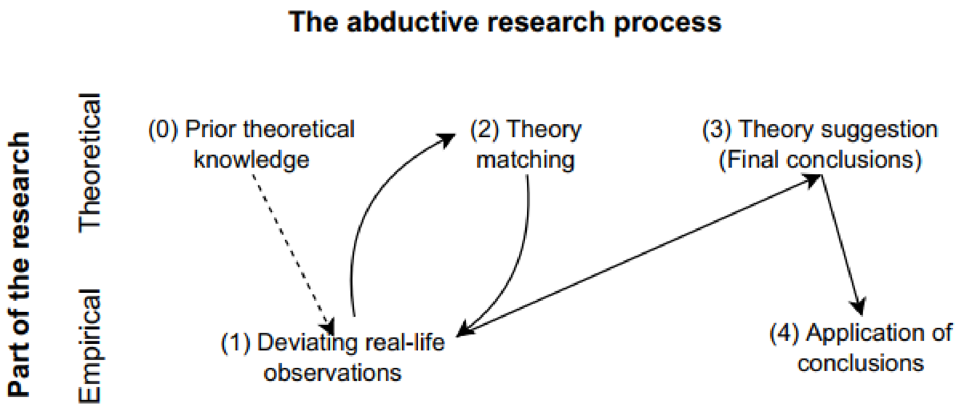


Figure 4-2 The abductive research process. Retrieved from: Kovács & Spens (2005)

According to Håkansson (2013), two main categories exist for research methods: quantitative research and qualitative research. Quantitative research requires large data sets and uses statistics to test and validate the hypothesis, and it is most suitable for theory-testing studies. On the other side, qualitative research commonly uses smaller data sets that are enough to reach reliable results. This method is suitable for understanding meanings, opinions and patterns to develop hypotheses, theories or frameworks. Since the main goal of this PhD research work is not to develop or test theories or hypotheses nor to do statistical testing, the qualitative method was used.

4.3 Case study design, selection and units of analysis

4.3.1 Case study design

An area that has been debated over the years on case studies is related to the conflict between seeking innovative theoretical insights provided by the richness of a single case study or a replication logic for multiple case studies (Piekkari et al., 2009). The selection of the cases and companies inside the cases, as well as the number of cases and unit of analysis, are critical steps in conducting case study research (Kahkonen, 2014). On the one hand, for a limited set of available resources, sometimes, the fewer the cases, the more opportunities for depth of observation are provided (Voss et al., 2002). Thus, single case design is known for its attention to context and descriptive power (Shakir, 2002). It is highlighted especially in studies carried out by researchers following more interpretivist or critical realistic philosophical perspectives. However, some limitations of conducting single cases include misjudging a single event's representativeness or reducing external validity (Caniato et al., 2018).

On the other hand, the use of multiple case studies is considered to increase the methodological rigour of the study through the strength, precision, stability and validity of the findings (Shakir, 2002), allowing to increase external validity and helping guard against observer bias (Voss et al., 2002). Even though for the same level of a limited set of available resources, Caniato et al. (2018) argue that a multiple case study design implies reducing the depth per case, Yin (1994) highlights that evidence from multiple case studies usually is considered more compelling. Considering the positivist philosophical assumption underpinning this exploratory research work and following Eisenhardt (1989) and Yin (2009), multiple case studies were selected, given the ability to increase the robustness of the findings. Furthermore, the researcher followed the following Yin's (2009) research design logic (Figure 4-3).

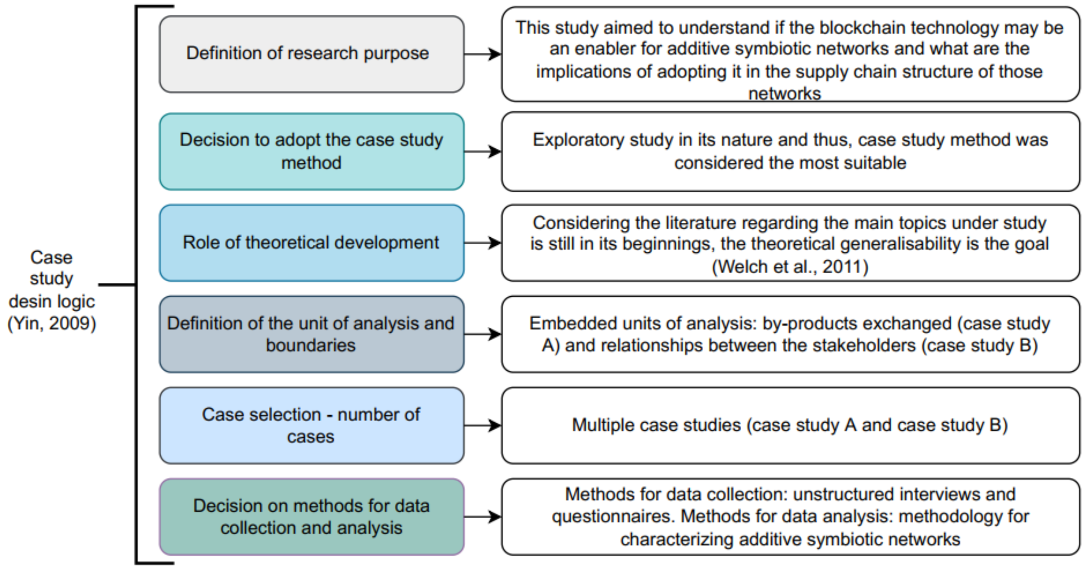


Figure 4-3 Case study design logic followed in this PhD research work

4.3.2 Case study selection

As there are a variety of AM processes and technologies, there is a significant variety of materials used as inputs, and also, the nature of these materials is dependent on the specific type of AM process or technology to be performed (Ford & Despeisse, 2016). The European Commission has identified plastic materials as a priority area (Cruz Sanchez et al., 2020) and creating a context that improves the quality and economics of plastic recycling are important issues to solve to create value from these secondary resources. Polymer materials are a key topic in the AM field and are the most used type of materials. During the raw material processing stage, there is an opportunity to rethink about how specific types of raw materials are processed to minimize the resources needed to bring them into usable form as inputs for manufacturing processes (Ford & Despeisse, 2016), and here, AM also offers a great opportunity for converting by-products and waste into value-added products (Ferreira et al., 2021).

The manufacturing landscape is constantly changing. One of the most critical drivers, according to Ford & Despeisse (2016), in this change is the emergence of advanced manufacturing technologies that enable more resource and cost-efficient small-scale production and, additionally with other prominent trends such as personalization, prosumption and servitisation, is taking companies to start to rethink how and where they conduct their manufacturing activities. Having associated remarkable advantages, such as being viewed as an environmentally sustainable manufacturing technology that has the potential of reducing up to 525.5 metric tons of total carbon dioxide, the AM global market tendency is to increase in the following years, according to Tan et al. (2020). The materials used in AM technologies provide opportunities for improvements in sustainability, as already shown in Chapter 2. Moreover, considering the fundamental research questions related to ISNs and the AM industry and the selection criteria presented in chapter 1, a focus on companies that work with AM technologies and incorporate plastic wastes or recycled materials in their processes was considered to be suitable.

Some authors, as Rowley (2002), argue that there is no simple answer to the question of how many cases should be included in a multiple case study approach. According to Shakir (2002), it is widely accepted that the number of cases can be decided in a trade-off between the depth and breadth of the case study approach, and thus, the sample does not need to be representative of a larger population.

According to Eisenhardt (1989), multiple case studies (preferably between 4 to 10) can provide a better basis for generalization. However, Yin (2009) disagrees with this, highlighting that instead of thinking about the cases as a sample, they should be viewed as the opportunity to shed empirical light on some theoretical principles or concepts, and at least two cases should be conducted. In this PhD research work, a logic "*à lá Yin*" was followed, and two case studies were conducted to give insights into theoretical and empirical concepts around the development of additive symbiotic networks. Two cases related to the AM industry were considered relevant to study the development of additive symbiotic networks and to understand the requirements to adopt blockchain technology in such settings and its implications in the supply chain structure of those networks.

Piekkari et al. (2009) highlighted that the selection of additional cases should be made according to whether similar (literal replication) or different (theoretical replication) results may be predicted with the emergent theory. Additionally, Kahkonen (2014) highlighted that multiple cases allow for comparisons between the cases themselves and provide a stronger base for theory building or extension. However, even though in this

PhD research work from a literal replication logic, the two case studies could be chosen to have similar settings and expected to achieve similar results (Shakir, 2002), the aim was not to compare the cases between themselves. As highlighted in Chapter 1 (Figure 1-2), the case studies intended to answer different research questions since both represent different additive symbiotic networks from different countries and at various stages of the industrial symbiosis process. The two case studies were selected due to their representativeness of additive symbiotic networks:

- Case study A refers to the "*From Trash to Treasure*" project that occurred in 2019 and is already closed. It comprises a company called re:3D, located in Texas, USA, that uses production wastes from other industries to produce 3D-printed pieces of furniture.
- Case study B refers to a network that was created by a start-up named B-PET. This company is located in Buenos Aires, Argentina. It supplies 3D printing technology, equipment and services, allowing other organizations to incorporate plastic waste streams to produce recycled 3D printing filament.

4.3.3 Units of analysis

Yin (2009) defined four types of case study designs established based on whether a single case or a multiple case design is used and whether it is a holistic design (with a single unit of analysis) or embedded design (with multiple units of analysis) (**Erro! A origem da referência não foi encontrada.**).

Guetterman & Fetters (2018) highlighted that a holistic case study design uses a global-level unit of analysis, and an embedded case study design involves units of analysis that come from multiple levels (**Erro! A origem da referência não foi encontrada.**). In this PhD research work, a multiple case study design was selected considering a holistic unit of analysis. Considering the main research questions that this PhD research work intends to answer (**RQ1** – *How to promote ISNs in the AM context?;* **RQ2** – *What are the requirements to make use of blockchain technology in an additive symbiotic network?* and **RQ3** - *What are the implications of blockchain technology adoption in the supply chain structure of an additive symbiotic network?*), the symbiotic network of each case study was considered itself as the main unit of analysis.

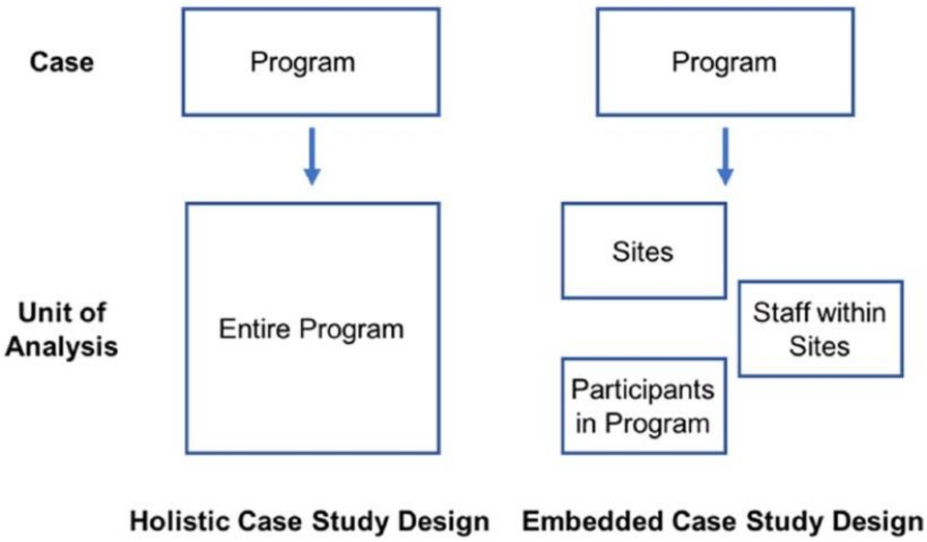


Figure 4-4 Units of analysis for holistic and embedded case study designs. Retrieved from: Guetterman & Fetters (2018)

Another important decision that needed to be considered was, within each case study, to decide which companies would be involved in the research work. Considering the methodology presented in sub-chapter 2.2.4, the focal organisation was first defined for each case study. After that, it was asked to each focal organization to designate a set of companies that would also be involved in the symbiosis network. The main selection criteria were their relevance to providing insights into the flows and resources exchanged within the networks. The main stakeholders in each case study are presented and described in detail further in Chapter 5.

4.4 Data collection and data analysis

4.4.1 Data collection

For both cases, qualitative data was gathered with the aimed to be to obtain a rich set of information that captures the complexity of the topic under research. Two types of data can be collected: primary and secondary data. Rabianski (2003) highlighted that primary data concerns information and facts gathered specifically for the purpose of the investigation under study. Additionally, secondary data relates to information and facts gathered not for the immediate study but for some other purpose and are usually a complement to the primary data.

Furthermore, data can be collected in various ways, considering different sources and strategies. Each data collection method has its merits and shortcomings. According to Karlsson (2016), the primary data source in case research is structured interviews, often based on interactions and unstructured interviews. Other data sources can include personal observations, questionnaires, reviews of archival sources or even informal conversations. In their review, Bluhm et al. (2011) concluded that interviewing is the most popular data collection method and that archival data was the second most popular, even though it was rarely described in most research papers.

On the one hand, questionnaires can reveal high-quality, usable data, helping to reduce the bias when providing anonymity and are a valuable data collection source to be used when the target audience, even if geographically spread, can be clearly identified and defined and when the majority of the respondents know what is asked of them (Marshall, 2005). On the other hand, according to Gill et al. (2008), unstructured interviews usually do not reflect any preconceived theories or ideas and are performed with little organization. They may simply start with an opening question and will progress based, mainly, upon the initial response. However, these types of interviews may be very time consuming and challenging to manage or participate in since there is little guidance on the topic being talked about. Thus, their use is generally only considered when little is known about the subject area or when "in-depth" is required.

In this PhD research work, two case studies are developed concerning two different additive symbiotic networks. For both cases, primary and secondary data sources were used to collect data. Specifically, since this work is highly exploratory and considering the methods presented in Table 2-6 in sub-chapter 2.2.3, questionnaires and unstructured interviews were used to identify the stakeholders involved. These are described in detail in Chapter 5, within the data collection sub-chapters. A methodology based on the stakeholder value network (as presented in sub-chapter 2.2.2) was selected for characterizing the stakeholders involved in the networks, followed by actor-linkage matrices (called value flow matrices) to represent the relationships between them. The methodology for characterizing additive symbiotic networks will be presented in detail in the following sub-chapter.

Additionally, secondary data was also collected from the websites of the companies involved in each case study. The questionnaires were sent to the stakeholders involved in the networks, and unstructured interviews were taken with the experts from the focal organization of each network to support the researcher (available in Appendix B - Questionnaire B.1, Questionnaire B.2, Questionnaire B.3 and Questionnaire B.4). Within this PhD research work, both cases studies were simultaneously conducted, meaning that during each research phase, the questionnaires and unstructured interviews were performed concurrently in the four companies involved.

Within case study A, a total of 25 events (which included emails, two questionnaires and an unstructured interview) occurred. The interview of approximately half an hour of duration was conducted with the respondent from the focal organization of the network.

Within case study B, a total of 40 events (including emails, three questionnaires and two unstructured interviews) occurred. The two interviews, which lasted for approximately 1 and 1 hour and a half, respectively, were also made to the respondent from the focal organization of this network. For case study A, the interviews were made in the interviewee's native language, American English, and in case study B, in the researcher's native language, Portuguese. The principal researcher conducted the unstructured interviews.

Additionally, to limit expert bias in the research results and to ensure data triangulation, other sources of data were used, namely, secondary data sources such as companies' websites, reports, process descriptions and academic papers.

According to Yin (2009), one of the most critical advantages of using multiple sources of evidence is the development of converging lines of inquiry, allowing the emergence of the findings. The author highlights that triangulation of multiple sources of evidence is important to ensure the reliability and validity of the study, and thus advanced preparation is critical to ensure that multiple sources of evidence are considered.

In the following chapter (Chapter 5), there is a sub-chapter dedicated to the data collection process for each case study. The process is described in detail. For both case studies, experts from the companies involved in each network were selected to answer the questionnaires and be available, if necessary, for unstructured interviews. Since not all companies have similar functional and organizational structures, people with different functional responsibilities were chosen for each company.

4.4.2 Data analysis

Data analysis involves several stages of review, categorising, tabulating and recombining evidence to determine meaning related to the initial research aim, research questions, objective of the research and issues (Miles & Huberman, 1994; Yin, 1994). According to Miles & Huberman (1994), the main goal of data analysis is to produce credible conclusions. It is critical to ensure that all data is treated equally and without bias while keeping its original context and meaning (Yin, 1994). For this PhD research work, the data analysis starts after the first questionnaires with the focal organizations of each network within each case study and then continues along the entire data collection phase. Thus, the research focus was preserved, and the excess data was restricted.

Within the scope of this PhD research work, the data analysis conducted for both case studies related to the methodology for characterizing additive symbiotic networks presented in the past sub-chapter 2.2.4. This methodology is used for different purposes in the case studies. For case study A, it is necessary to characterize the additive symbiotic network under study, including its main stakeholders, value flows exchange, and main activities performed in the network. For case study B, there is a need to characterize the additive symbiotic network under study to compare the power distribution among the stakeholders involved in the network before and after adopting blockchain technology.

According to Miles & Huberman (1994), data analysis is an interactive process that combines data reduction, data display and conclusions. Data reduction deals with focusing, condensing, simplifying, and structuring the data into manageable units. The data display stage is related to how data is presented and communicated. After, the data analysis stage should consider enfolding prior knowledge, rival theories or alternative explanations. Displays of data can be a useful way to present the information systematically (Karlsson, 2016). In this PhD research work, the main outcome of the methodology used to characterize an additive symbiotic network is a value flow matrix that is presented for both case studies.

To draw conclusions from the data, Yin (2002) proposes a within-case analysis followed by a cross-case analysis (Eisenhardt (1989). However, in this PhD research work, the aim of using multiple cases was not to compare the cases to each to achieve a generalizable explanation or theory. Rather, the case studies are used in different phases of the research approach and intend to address different research questions and show different insights around this relatively new phenomenon. Thus, a cross-case analysis –which aims to expand the investigation to a more robust understanding of the phenomena being studied - was not considered to be required for this exploratory PhD research work.

Concerning the generalizability of the results, the concept of generalizability has different meanings in different approaches and related research issues. This PhD research work intends to achieve an analytical generalization of the results. Unlike quantitative studies, qualitative studies rely on analytical generalization rather than statistical generalization (Karlsson (2016). The analytical generalization is the generalization of a specific set of results to some broader theory (Shakir, 2002). To Karlsson (2016), in qualitative research, the case selection aims to find cases of particular interest for the research topics under study, and the analytical generalization can be made by comparing them with similar cases or theories.

The data analysis process is detailed for each case study in Chapter 5.

4.5 Case study quality and limitations

According to Welch & Piekkari (2017), settling on a single set of criteria for judging qualitative research is neither desirable nor possible. Evaluative criteria are produced by the research community – institutional structures and traditions, dominant practices, and intellectual influences. Since in this PhD research work, a positivistic philosophical assumption is being followed, the quality criteria for assuring the quality of the work follow qualitative positivism from a pluralist criteriology – quality criteria and appropriate procedures vary on the philosophical paradigm being followed (Welch & Piekkari, 2017). Thus, in order to ensure the case study quality in empirical research, Yin (1994) proposes four measures to be considered: validity of construct, internal validity, external validity and reliability (Table 4-1).

Thus, in this PhD research work, the following measures were taken to ensure the case studies' quality:

- **Construct validity** – in both case studies, different sources of evidence were used, namely, secondary and primary data were collected from distinct sources. The analysis of the questionnaires and unstructured interviews allowed to map both networks and create value flow matrixes that characterize them, establishing a chain of evidence.

- **Internal validity** – in both case studies, the main findings and conclusions were presented and validated among all the entities involved in the study to ensure that relevant variables were included and the data was adequately analyzed.

Table 4-1 Qualitative positivism criteria to ensure the quality of the study

Criteria	Definition (
Construct validity	Ensures consistency between the constructs and their measures [(b)] (correct operational measures [(a)]).
Internal validity	Ensures a relationship between cause and effect [(b)] – the extent to which a causal relationship can be established whereby certain conditions are presented to lead to others [(a)] [(c)].
External validity	Specifies the domain to which the findings may be generalized [(b)] (if the study's findings can be extended beyond the immediate case study [(a)] [(c)]).
Reliability	Demonstrates that the findings will hold if the study were replicated [(b)].
Note: [(a)] Voss et al. (2002); [(b)] Welch & Piekkari (2017); [(c)] Yin (1994)	

- **External validity** – the case studies' main objective was not to generalise the results. Instead, it aimed to explore adopting a disruptive technology into news domains – the additive symbiotic networks. The unit of analysis was clearly defined, and the case study scope was given to support the results to comparable cases.
- **Reliability** – Even though a specific case study protocol was not developed, the questionnaires sent to the experts involved in the research were developed using existing measures and constructs from the existing literature. Specifically, this research applies the methodology from Ferreira et al. (2019) for the development and evaluation of additive symbiotic networks.

Despite assuring the case studies' quality, like other research methodologies, the use of the case study approach is shortcoming by a set of limitations. One of the main limitations of this PhD research work concerns with the generalizability to which this study can be extended. Even though multiple case studies were conducted, the aim was not to generalize or compare them but to provide new insights and foster knowledge on a phenomenon that is not fully understood yet. Another limitation may be related to using different cases to assess different research questions and, thus, with differing conclusions. However, even though both cases represented additive symbiotic networks, the networks themselves were at different stages at the time of this PhD research work.

The network from case study A was created from a project that was already concluded, and the network from case study B was being developed at that time.

Furthermore, as Eisenhardt (1989) and Yin (1994) suggested, a cross-case comparison was not performed; thus, this study's main conclusions cannot be generalised to other contexts. However, this PhD research is exploratory in its nature, the case studies can be considered as a form of “natural experiment”, offering a high degree of internal validity in which the lack of generalizability is not a concern since the theoretical generalizability is the ultimate goal (Welch et al., 2011).

4.6 Chapter summary

This chapter has presented the research methodology used in this PhD research work. The researcher’s positivistic ontology and epistemology were highlighted and justified. An explanation for considering an abductive approach and using the case study method to investigate the research topics is also provided. Furthermore, the factors related to the case study design are explained and justified, namely, the case study selection, definition of the unit of analysis and data collection and data analysis techniques. The measures considered to ensure the quality of the case study (construct validity, internal validity, external validity and reliability) are presented, as well as a discussion regarding the main limitations concerning the research methodology used.

Table 4-2 comprises the summary of the case study research design that was used in this PhD research work.

Table 4-2 Case study research design used in the PhD research work

Case study research design	Description
Theoretical aim	Exploratory
Case selection criteria	Representative example
Multiple vs single case	Multiple case approach
Level of analysis	Holistic case study design
Unit of analysis	Additive symbiotic network
Data gathering techniques	Questionnaires Unstructured interviews Secondary data sources (websites, available online documents)
Data analysis	Transcription of the information with subsequent review and validation by the experts Matrix of value flows
Case study quality	Use of multiple sources of evidence Triangulation of information gathered at the different entities Key experts’ review and validation of the findings

5

CASE STUDIES

After defining the research methodology used in this PhD research work, two case studies were conducted with different research objectives. This chapter aims to present and analyze the data collected during Phases II and III of the research approach (defined in sub-chapter 1.3). The chapter is divided into two main sub-chapters for each case study. Each of these sub-chapters provides an overview of the case studies and a detailed description of the data collection process.

For both cases, their inherent additive symbiotic networks were analyzed and characterized. Identically, both cases represented an additive symbiotic network under the implementation phase (phase V of the framework for the industrial symbiosis creation - Table 2-1). Even though plastic wastes are exchanged between the stakeholders involved in both networks, their purpose differs in each network. In case study A, wastes from one company (after grinded) are directly used in a 3D printer that is prepared to receive this type of materials inputs (the Gigabot-X). In case study B, post-consumer recycled waste streams (after being transformed into pellets and flakes by an approved national recycler entity) are used to produce filament to be used in 3D printers.

The adoption of blockchain technology was explored for each case study with different goals and is also presented and debated in each case study's sub-section. Finally, the main research findings are discussed at the end of each sub-section.

5.1 Case study A

This sub-chapter contains the description, analysis, and results from case study A. The case under study was conducted during Phase II of the research and aimed to answer the second research question: **RQ2** - *What are the requirements to make use of blockchain technology in an additive symbiotic network?.*

5.1.1 Case study's description – "From Trash to Treasure"

In Phase II of the research approach, a first exploratory case study related to an additive symbiotic network was carried out. The AM technology in this case study is supplied by a company located in Texas, USA, that sells 3D printing equipment and services using plastic waste streams as a secondary raw material. The company under study is re:3D. This company is pioneering innovations to reduce the cost and social barriers to 3D printing while enabling circular economies and changing traditional supply chains. With customers spread in more than 50 countries worldwide, re:3D's main product is Gigabot, the world's largest industrial fused filament fabrication 3D printer. Recently, re:3D modified this printer to enable 3D printing from pellets and reclaimed plastic waste, allowing sustainable, affordable, and locally driven manufacturing.

The company introduced the AM technology in 2013 and currently has two types of 3D printing equipment: i) Gigabot X (GBX) pellet printers; ii) Gigabot 3+ filament printers. re:3D uses both fused granular fabrication and fused filament fabrication technologies. The company has its fabrication facility located in Austin, Texas, and beyond producing 3D printers, it also offers 3D printing contract services, design, consulting, and education. Printing with a bigger nozzle, whereas utilizing pellets or flake, is 5 to 10 times more economical when compared to the traditional filament. The GBX's larger nozzle can decrease printing time up to 17 times compared to fused filament fabrication printers. The GBX can print with 1/8" plastic granules melting below 270ºC, and in this way, decreasing the dependence on printing using filament at the same time as supporting plastic granule mixing. A depiction of GBX with some of its features is presented in Figure 5-1.

Within the scope of this PhD research work, a focus was given to one specific project in which the company took part – the "From Trash to Treasure" project, which made it possible to print goods directly from plastic waste. This project is an example of an additive symbiotic network where different stakeholders exchange value between them. The additive symbiotic network itself was considered to be the unit of analysis.

The case study comprises four stakeholders (Table 5-1): i) re:3D – a start-up that produces and sells 3D printing services and technologies to valorise waste; ii) HID Global - a manufacturing company that produces ID cards (where the by-product is generated); iii) Austin Resource Recovery - the organization that promoted an event which allowed for the different stakeholders to meet and iv) Austin Habitat Humanity ReStore - the store where goods printed from the by-product were displayed. These entities were selected for this work due to their potential to create and develop an additive symbiotic network.

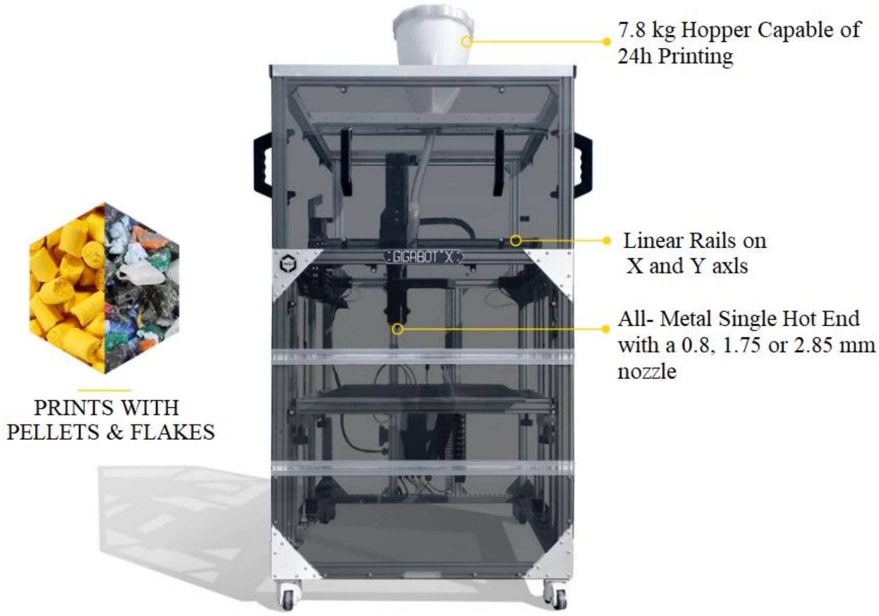


Figure 5-1 Gigabot X printer. Retrieved from (re:3D Inc, 2020a)

Every year, the Austin Resource Recovery department hosts an event called the Austin [Re]Verse Pitch for companies within the Austin community that are creating waste that could be used in other areas of business or sectors (austintexas.gov, 2020). Among the companies that participated in this event in 2019, HID Global, a security and identity company, has pitched about PC sheets. This waste results from producing identification cards in the company's factory and is made in significant amounts, approximately around 410 kg per week (HID Global, 2021b). During the competition, re:3D was able to pitch the "Design: by re:3D" for a line of furniture – The Austin Habitat for Humanity ReStore, where home goods and art pieces were intended to be printed on GBX directly from the HID's PC sheets.

Small vases were included among the products produced by re:3D from the PC sheets. The maximum speed of extrusion rate for the GBX printer is 0.8kg/hour. Considering that the weight of a small vase is 0.8kg, it will take 1 hour for the printer to print one unit of product. re:3D determined that 95% of the PC sheets that go into the granulator are printed. However, the extra 5% is lost in processing. Again, if a small vase is 0.8 kgs, there is needed for 0.842 kgs of PC sheets per vase (0.042kgs are lost in processing).

Table 5-1 Stakeholders' description for case study A

Stakeholders	Description	Activity
re:3D	Start-up that produces and sells 3D printing services and technologies	3D printing services, technologies, and printers
HID Global	Manufacturing company that produced ID cards	Company whose main product line is secure identity products. The production of such products generates PC wastes that can be used as by-products (around 410 kgs of clean PC waste per week)
Austin Resource Recovery	Austin city's waste management utility	Promoted an event called "Austin [Re]Verse Pitch Competition"
Austin Habitat for Humanity ReStore	Non-profit home improvement stores and donation centres	Store that displayed the first pieces of furniture printed from plastic waste

As Figure 5-2 shows, it all started in 2018 when re:3D had the opportunity to fund the creation of the GBX 3D printer. In 2019 the pitch made by re:3D was the winner of the Austin [Re]Verse Pitch Competition, and in 2020, almost a year later, the first pieces of furniture printed from PC sheets were being displayed. This study was developed in the year 2020, and, at that time, this project was under a trial phase, meaning that the first pieces of furniture created by re:3D were being featured to assess possible interest.

As highlighted in sub-chapter 2.1.1 (in Table 2-1) the industrial symbiosis creation process comprises six main phases that are aligned with the case study under analysis:

- "Phase I - Preliminary assessment", "Phase II- Engage businesses", and "Phase III - Find synergy opportunities" are related to the [Re]Verse Pitch competition phase of the project, where the network of contacts is established, and the first interactions between stakeholders occur.
- "Phase IV- Business feasibility" is linked to the last stage of the [Re]Verse Pitch Competition phase before displaying the first pieces of furniture.
- "Phase V - Implementing transactions" translates the project's current state at the time of this study– the phase of implementing transactions of resources among the symbiotic stakeholders.

It should be noted that within the scope of this PhD research work, the phases related to the environmental, social, and economic impact assessment were excluded from the analysis.

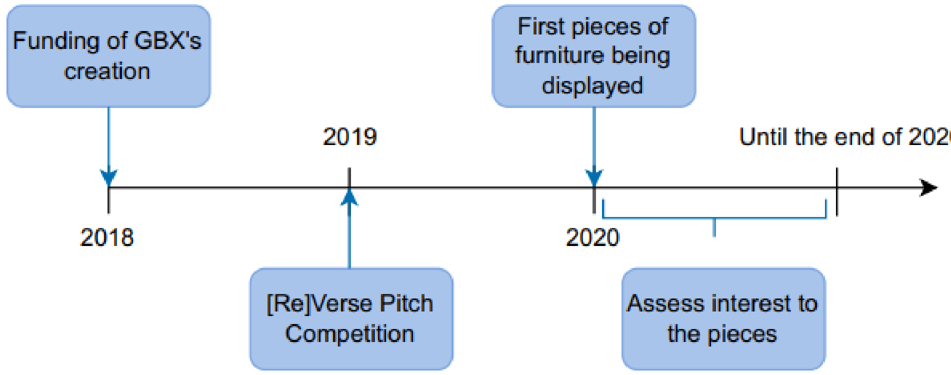


Figure 5-2 Timeline of the project “From Trash to Treasure”

5.1.2 Data collection

Secondary and primary data were collected using distinct methods and sources. Regarding the primary data (Table 5-2), the researcher conducted unstructured interviews with the experts representing the stakeholders involved in the network. The experts' profile is also available in Table 5-2. It is critical to highlight that the Austin Resource Recovery stakeholder is represented in this study by the Austin Young Chamber, a Chamber of Commerce and one of the entities involved in the Austin [Re]Verse Pitch Competition organization. Moreover, the Austin Habitat Humanity ReStore is represented by the company re:3D.

Considering the network of the case under study, four questionnaires (Questionnaire B.1, Questionnaire B.2, Questionnaire B.3 and Questionnaire B.4) were devised to capture the stakeholders' different perspectives. The main aim was to map the stakeholders and resources in the network and identify and quantify the value flows exchanges between them. In the first stage, Questionnaire B.1 was developed for re:3D to identify and map the main stakeholders and wastes exchanged, allowing a characterization of the overall network. In a second stage, to identify and quantify the value flows and transactions, customized questionnaires (Questionnaire B.2, Questionnaire B.3 and Questionnaire B.4) were sent to each stakeholder (re:3D, HID Global and Austin Young Chamber, respectively).

Secondary data was collected from the companies' reports on the project "*From Trash to Treasure*", specifically, an executive summary of the event Austin [Re]Verse Pitch (re:3D Inc, 2019), along with relevant data from the companies and organizations websites. This data set was used to support the design of the network's first draft and identify primary stakeholders.

Table 5-2 Primary data collection for case study A

Objective	Data collection	Stakeholder	Expert's profile	
			Function	Professional experience (years)
- Case study description - Identification of wastes and stakeholders - Identification of the focal organization	-Unstructured interview - Questionnaire B.1	re:3D	Co-founder & catalyst	20
- Value flow identification and quantification - Identification of transactions	Questionnaire B.2			
	Questionnaire B.3	HID Global	Environmental, Health and Safety Leader	5
	Questionnaire B.4	Austin Young Chamber	Circular Economy Program Manager	9

5.1.3 Data analysis

In order to answer to the second research question proposed in this PhD research work (**RQ2** - *What are the requirements to make use of blockchain technology in an additive symbiotic network?),* there is a need first to characterize the network under study, namely the value flows and the stakeholders. The methodology for value network mapping proposed by Ferreira et al. (2019) and presented in sub-chapter 2.2.4 (Figure 2-4) was followed, considering the criteria (Table 2-7, Table 2-8 and Table 2-9) developed for quantifying the value flows. This allows to create a value flow matrix which is the ultimate result of the value flow mapping to assess the power distribution of the network's stakeholders.

The following paragraphs describe the different steps of the mythology to create a value flow matrix characterizing the network under study.

1. **Identification of the stakeholders in the network**

The first step was to determine the focal organization and the stakeholders involved in the network, through primary data collected from the unstructured interview and Questionnaire B.1 and secondary data. The focal organization is responsible for conducting negotiations and investigations and regulating the symbiosis's implementation and operationalization. In the case under analysis, the re:3D was the company that had a 3D printer able to print directly from plastic waste - the GBX printer. The company developed a whole system that allowed it to grind, dry and feed the plastic waste into the printer (re:3D Inc, 2020b). It is the entity responsible for all necessary treatment before incorporating the waste and transforming it into new products. Also, it is responsible for finding partners that could provide them with plastic wastes as secondary raw materials and others that would be able to sell their final products. Therefore, in this study, the re:3D was considered the focal organization.

Different entities interacting with each other constitute the ISN. These entities are the so-called stakeholders. There are different types of stakeholders: i) direct partners - the ones directly involved or plan to be involved in the exchange of resources; ii) indirect partners - the ones that can develop an indirect type of collaboration however necessary to support the exchange of resources within the network (Ferreira et al., 2019). In the case study, the direct partners are:

- **HID Global:** Headquartered in Austin, Texas, HID Global has over 3 000 employees worldwide and operates international offices that support more than 100 countries (HID Global, 2021a). HID powers the trusted identities of the world's things, people, and places. Every day millions of people use HID products and services to securely access physical and digital places. HID products are used to verify transactions, open doors, track assets, find information, digital access networks, and connect with others.
  As a material supplier, HID Global participated in the fourth [Re]Verse Pitch Competition in 2019. The company produced at that time around 1640 kgs per month of PC skeletons from dye-cut ID cards (Reverse Pitch Competition, 2019). All the material was being sent to a landfill, and HID Global was looking for a more sustainable solution. This type of waste stream was possible to print with because PC is a very common 3D printing material, and the company's filament printing on GBX prints with PC regularly. Also, all the production process of the identification cards is done in a "clean" environment, which means that the waste

is extremely clean (one of the advantages of using it because dirt can cause clogs and other issues in the printing process).

Before using the PC sheets in a 3D printer, there is a need for waste treatment: collection, stacking, grinding, drying, sifting, and printing. The company re:3D is responsible for all these processes associated with waste recycling. Within the symbiotic network, the company HID Global can be seen as responsible for producing the by-product used to make furniture. HID Global provided to re:3D, within the *From Trash to Treasure* case study, approximately 907 kgs of PC sheets resulted from creating ID cards.

- **Austin Habitat for Humanity ReStore:** located in Austin and San Marcos, the Austin Habitat for Humanity ReStore is a non-profit organization with a donation centre and a discount home improvement store. The company is committed to increasing access to low-cost building materials for the community and home improvement supplies and redirecting valuable and reusable items from landfills (ReStore, 2021).

  At the Austin location, approximately 6,44 km away from the re:3D's location, the company positively impacts their community by reusing, reselling, and recycling materials. The company can recycle different types of materials from various metals, wood, paper, cement, ceramic, glass, plastic, and many others. Within the "*From Trash to Treasure*" project, the ReStore teamed up with re:3D to sell pieces of furniture, décor and other household items from plastic waste and reclaimed materials – namely, the small vases. The ReStore also allowed re:3D to install a small industrial grinder in one of their installations for grinding the PC sheets into PC flakes. However, the transportation of the PC flakes and their use in the 3D printer is re:3D's responsibility.

  The pieces of furniture, including the small vases, started to be displayed in 2020. However, since it is a trial period, the sale would likely be negative at the moment, but with labour, there is expected to be positive revenue.

As indirect partners, it was considered:

- **Austin Resource Recovery -** The Austin Resource Recovery, which within this case study represents the Austin [Re]Verse Pitch, is the only indirect stakeholder and is a non-profit subsidiary of the City of Austin. The Austin Resource Recovery department of the City of Austin offers a broad range of services designed to transform waste into resources while simultaneously keeping the community clean (austintexas.gov, 2020). These services include residential curbside collection of trash, recycling, composting, and yard trimmings. Two departments of the City of Austin, namely the Austin Resource Recovery Department and the

Economic Development Department, have joined efforts to launch the Circular Economy Program, which mission is to attract, grow and retain businesses, entrepreneurs, and non-profits, to attract investment, and to support the necessary infrastructure for resilient circular economy in Central Texas (austintexas.gov, 2019). The City of Austin Circular Economic Program and some community partners launched the [Re]Verse Pitch Competition. The competition is designed to inspire profitable new ventures while keeping materials out of landfills. The project "From Trash to Treasure" was the winning of the fourth annual [Re]Verse Pitch Competition. The Austin Resource Department is represented in this study by an expert belonging to the Austin Young Chamber.

2. **Identification of value flows**

The second step of the methodology is related to identifying value flows. The flows exchanged between indirect and direct stakeholders are represented in Figure 5-3, with dashed arrows and filled arrows, respectively. To identify the flows, primary data was used, namely data from part I of Questionnaire B.2, Questionnaire B.3 andQuestionnaire B.4.

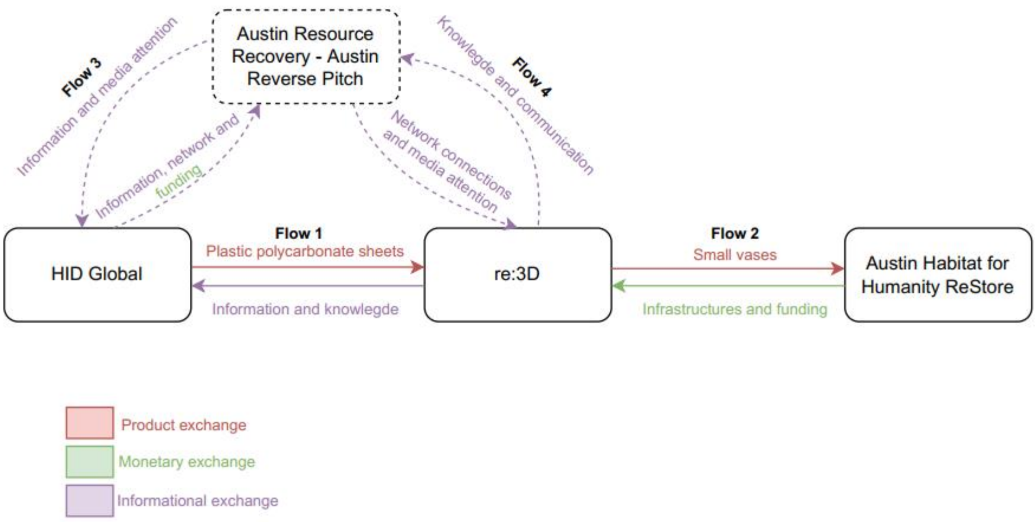


Figure 5-3 Value flows exchanged among the stakeholders in case study A

Each value flow is constituted by a two-way relationship – the direct and the reciprocal flows (both represented in Figure 5-3). The reciprocal flows represent the inverse relationship of the direct ones.

The "*From Trash to Treasure*" value chain can be modelled through a network with different resources traded in the direct flows: PC sheets, small vases, knowledge and communication and information and media attention. The direct flows, as well as the respective resources exchanged, can be described as follows:

- **Direct flow 1 –** PC sheets are a by-product from HID Global, resulting from producing ID cards. This waste was meant to be sent to a landfill. However, it was noticed that the focal organization of this network, re:3D, could use these by-products as a material input to produce furniture pieces, for example, small vases, after receiving the necessary treatment.
- **Direct flow 2** – After receiving the by-product, the focal organization is responsible for using it as a material input in an AM process to produce the new pieces of small vases. These pieces are then sold in a store called Austin Habitat for Humanity ReStore.
- **Direct flow 3** – The Austin Resource Recovery does not have any monetary revenue; however, it helps hosting events like the Austin [Re]Verse Pitch Competition because of their networking and relationships with material suppliers and innovators. Within the *From Trash to Treasure* case study, the HID Global communicates the amount and characteristics of the wastes produced, reviews the business plans of each innovator, and selects which initiative they would likely be more receptive to.
- **Direct flow 4** – the focal organization is responsible for providing the Austin Resource Recovery with information about the utility and possible uses of the wastes. Also, the focal organization helps Austin Resource Recovery get media attention and exposure by participating in and winning the competition.

Intrinsic to all the direct flows above-mentioned, there are the reciprocal flows, specifically:

- Reciprocal flow 1: information and knowledge (given by the focal organization to HID Global on how to use the PC sheets wastes as a secondary raw material in 3D printers to produce new products).
- Reciprocal flow 2: infrastructures and funding (the ReStore allowed the focal organization to install a grinder in their installations for grinding the PC sheets before incorporating them in the 3D printer, and also, a percentage of the sales accomplished by the ReStore is given to the re:3D company).

- Reciprocal flow 3: network connections, media attention and exposure (the Austin Resource Recovery allows for interactions between companies that produce wastes and companies that can use those wastes as materials inputs for their processes, instead of deposing the wastes in the landfill).
- Reciprocal flow 4: Information, network and funding (the Austin Resource Recovery provides to the focal organization information about potential material suppliers and end-users costumers, enabling networking between the different stakeholders of the chain and funding the winner project of the [Re]Verse Pitch competition).

3. Quantification of value flows and value flow matrix

The “urgency” and “dependence” criteria, presented in Table 2-7 and Table 2-8, were used to quantify each value flow. Using Questionnaire B.2, Questionnaire B.3 and Questionnaire B.4 (namely data from part II), the experts representing the stakeholders involved were asked to quantify the scores for each criteria. The scores attributed to each value flow (both direct and reciprocal) are available in Appendix C. The value flow scoring is a subjective judgment; therefore, the aim was to determine if each stakeholder’s preference was truly captured.

The aggregated value scores, presented in Table 2-9, for the “urgency” and “dependence” criteria are used in this study. The combination of the two criteria generates an aggregated score that explores the power distribution among symbiotic stakeholders, i.e., the stakeholder's desire to be involved in the value exchanges. An explanation of how to assign the correct aggregated value for each value flow within the network is given, and it is available in Appendix C.

The value flow matrix is presented in Table 5-3 and characterizes the flows exchanged between the stakeholders in this additive symbiotic network. Each cell contains the designation of the value flow from the stakeholder in the row to the stakeholder in the column and the respective resources exchanged, and the aggregated score.

Table 5-3 Value flow matrix for additive symbiotic network A

From: \ To:	re:3D	HID Global	ReStore	Austin Resource Recovery
re:3D		**Flow 1 - reciprocal** Information and Knowledge (0.54)	Flow 2 - direct Small vases (0.51)	Flow 4 - direct Information and Media attention (0.54)
HID Global	Flow 1 - direct PC sheets (0.76)			Flow 3 - direct Knowledge and Communication (0.76)
ReStore	**Flow 2 – reciprocal** Infrastructures and Funding (0.76)			
Austin Resource Recovery	**Flow 4 - reciprocal** Information, Network connections and Funding (0.96)	**Flow 3 - reciprocal** Network connections and Media attention (0.76)		

5.1.4 Results and discussion

From the value flow matrix presented in Table 5-3, it is possible to characterize the main flows exchanged in this additive symbiotic network and conclude about the stakeholders' power distribution in that network. The aggregated score used to quantify the flows allows for the conclusion that there are stakeholders with different levels of power. More specifically, stakeholders re:3D and Austin Resource Recovery (that in this network corresponds to the ISN's facilitator) are deemed to hold the most power since they exchange the flow with the highest aggregated score.

Moreover, since the additive symbiotic network under study is in the implementation phase of the industrial symbiosis creation process, the value flow matrix presented in Table 5-3 also allows linking the value flows exchange to the two main activities involved in the implementation phase of the industrial symbiosis creation process. Thus, the main activities included in an additive symbiotic network:

- **Establish transactions** – Two types of transactions occur in this network:
    - Physical transactions of two resources: waste material PC sheets (concerns with the quantity and quality of the PC sheets used in direct flow 1) and small vases (quantity exchanged in direct flow 2).
    - Financial transactions that will correspond to the monetary value generated by selling the resource small vases (direct flow 2). Since the

project is under trialling by the end of this research, this financial flow was not included in the study.

- **Monitoring and reporting**: which correspond to information about the quantity of plastic waste used in the AM process, as well as to the knowledge about the use of AM technology (exchanged in reciprocal flow 1) combined with the information about the number of small vases produced, sold and respective price of sale (exchanged in direct flow 4).

Considering an additive symbiotic network that is under the implementation phase, the main activities performed in the network, and additionally considering the existing tools for supporting this implementation phase, as emphasized by Tseng et al. (2018), there is space to explore the adoption of the blockchain technology within such networks.

Blockchain technology provides many advantages that may promote the efficient implementation of the network that goes beyond its purpose of financial transactions (Gorkhali et al., 2020), such as distributed cloud storage, supply chain management, smart property, ownership, Internet of Things, among others (Xu & Viriyasitavat, 2019). However, even though there is an excellent opportunity to use blockchain technology within the scope of the additive symbiotic network, there is a need to understand if blockchain technology may be adopted in such settings, as highlighted by Gatteschi et al. (2018). More specifically, it is necessary to identify the requirements for using blockchain technology within an additive symbiotic network. Consequently, to find out if and how the blockchain technology could be applied to the additive symbiotic network under study, in the next bullet points, using the set of evidence collected in the case study, the requirements proposed in sub-chapter 3.2.1 are discussed and validated:

- A traditional database does not meet the additive symbiotic networks' needs. The conventional core logic databases of the stakeholders involved in this symbiotic network would need to have a specific function for the process of exchanging resources. The databases from all the stakeholders involved should have a function and be connected (with a team responsible for managing it) to allow the exchange of the different types of resources (PC sheets, small vases, monetary value, information, and knowledge) and thus, supporting the main activities of the network (establish physical and financial transactions and monitoring and reporting). Also, considering this case study, data about what a company typically assumes as "waste" (PC sheets quantity and quality) and data about the final product (small vases) need to be shared among stakeholders (flows 1 and 2).

- More than one participant needs to update the data in the database. At least two of the stakeholders involved in the network need to change and update the status of the transactions - the network founder and maintainer (which within this case study would correspond to Austin Resource Recovery), the moderator of the network (which would correspond to the focal organization – re:3D) and/or another stakeholder who audits all transactions and relations in the network (again, in this case study, this would correspond to the ISN's facilitator - the Austin Resource Recovery).
- No trust mechanisms exist between the additive symbiotic stakeholders. Since new relationships are being created and developed in ISNs, and most stakeholders belong to different industrial sectors, no trust exists between them. Furthermore, within this case study, the additive symbiotic network is an emerging network that arises from a competition. In this competition, different companies or organizations that do not have any kind of previous relationship created are introduced to each other, giving rise to the opportunity of trading resources between them. Since these different stakeholders did not know each other until the time of the competition, they did not have trust mechanisms developed and, thus, are expected not to trust each other.
- The additive symbiotic stakeholders do not trust a third party. The stakeholders involved in this additive symbiotic network would need to trust an entity outside their sector (responsible for making the agreements to support the transactions between the stakeholders) with whom they do not possess any established relationship.
- Data may or not be needed to be kept private. The data does not need to be private, so the stakeholders involved in the exchanges can monitor each transaction's status. More specifically, within this case study and when considering AM processes and products, there is a need to keep available information regarding the main AM processes and technologies used to transform the recycled materials into value-added products and information regarding the percentage of waste material used (reciprocal flow 1) should be accessible. Additionally, information such as quantity produced and sold regarding the final products (reciprocal flow 2) should also be available to all the stakeholders involved in the transactions.
- There might be a need to control who can make changes in the database. For example, reciprocal flow 4 has the highest value of the aggregated score. Consequently, it can be concluded that the Austin Resource Recovery and the re:3D are the stakeholders who hold the highest power in this network. On the

other hand, direct flow 2 has the lower aggregated score; thus, the ReStore stakeholder can be considered one of the stakeholders with lower power within this network. These differences in values regarding the power of the stakeholders can contribute to trust imbalances between them. Thus, there is a need to have a unique entity responsible for creating and maintaining the network that would correspond to the focal organization (namely, re:3D).

Figure 5-4 complies the decision path for the case under study, and it is suggested to use a permissioned blockchain.

At this stage and after conducting case study A, it is possible to answer the first research question that this PhD thesis intends to address (**RQ1** - *How to promote ISNs in the AM context?*).

As demonstrated from the systematic literature review presented in sub-chapter 2.1.3, plastic waste streams from other industries are used as material inputs for AM processes, promoting the creation and development of ISNs in the AM industry.

In this sense, and as highlighted from case study A, it becomes critical that the stakeholders that hold the most power within the network, the ISNs' facilitator and the AM technology provider, are involved in phase III of the industrial symbiosis creation process, that is, "*Find synergy opportunities*" (Yeo et al., 2019). According to the authors, it is necessary to have a "*matching mechanism based on process input/output stream: company-detailed data regarding the flows of resources, the "wants" and "haves", and specific data*" that within the case under study, corresponds to the competition promoted by the Austin Resource Recovery stakeholder (the ISN's facilitator). The case study also emphasizes that there is a need to make available a set of data for defining the AM systems in terms of waste or by-product characteristics (quantity and quality). This is made by the AM technology provider, that within this case study corresponds to the re:3D stakeholder.

Furthermore, evidence from case study A to conclude about the main activities performed in an additive symbiotic network, which correspond to: establishing transactions (related to waste materials, products and money) and monitoring and reporting (that includes AM processes control and knowledge about AM technology).

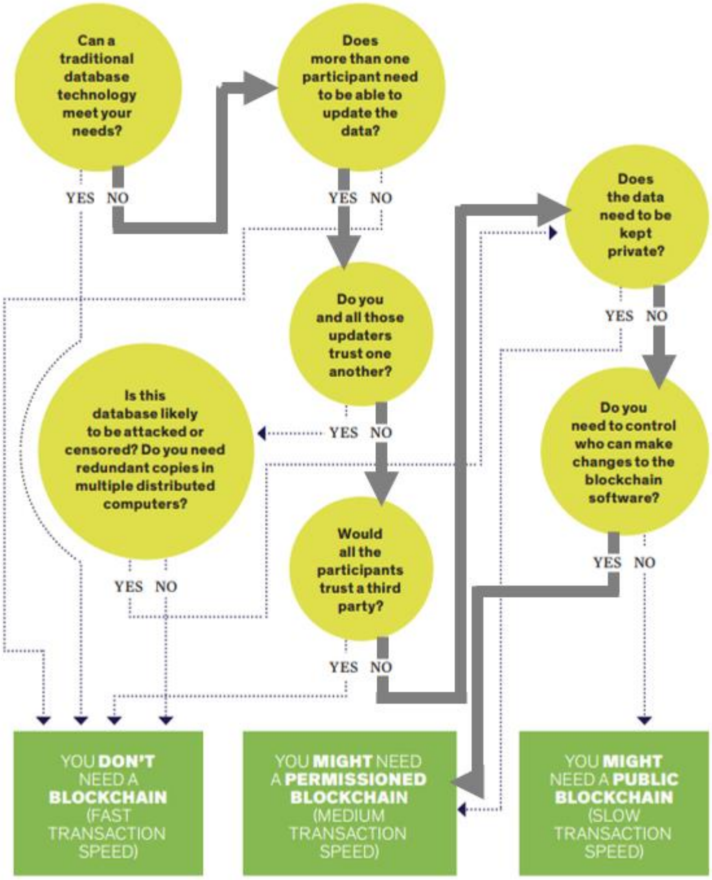


Figure 5-4 Can blockchain technology help to implement an additive symbiotic network? The decision path (i.e. arrows in grey) for case study A. Adapted from Peck (2017).

The second research question being addressed in this PhD thesis, **RQ2** – *What are the requirements to make use of blockchain technology in an additive symbiotic network?* can also be answered at this stage after concluding case study A. The requirements to adopt blockchain technology in an additive symbiotic network are validated and correspond to: i) the database should allow all the stakeholders to connect and support the main activities involved in an additive symbiotic network in the implementation phase of the industrial symbiosis creation process; ii) at least two of the stakeholders in the network need to update the data in the database; iii) no corporation or trust mechanisms exist between the stakeholders; iv) the stakeholders do not trust in a third party, v) data does not need to be kept in private and vi) there is need to have an entity responsible for making changes in the database.

Case study A has highlighted the use of a permissioned blockchain to enhance the activities corresponding to establishing transactions and monitoring and reporting involved in an additive symbiotic network under the implementation phase. These results are aligned with previous findings regarding the use of blockchain technology in ISNs' development (Gonçalves et al., 2022. Likewise, it gives evidence of the adoption of blockchain technology as an enabler technology of additive symbiotic networks.

Results from case study A show that, even though the blockchain may be an enabler for promoting additive symbiotic networks, adopting a new technology may bring further technological implications. Such implications can be minimised by implementing a proven blockchain technology that can be deployed within a very short time within the infrastructure of a cloud service provider. Nevertheless, a server within a permissioned blockchain must be set up per entity, employees must be trained in the use of the system, and the IT staff must be trained in maintaining the servers' node. On a positive note, interfacing between entities that use the same blockchain technology is streamlined and requires only an effort in the initial setup. On the other hand, managerial implications also arise with the adoption of new technologies, such as AM or blockchain. Namely, since ISNs aim to promote the exchange of resources among different stakeholders from different value chains or industries, it is critical to put into action proper mechanisms to support the material flow and relationships, as well as to manage trust imbalances between stakeholders. Non-profit organizations and company managers can use the blockchain as a supporting technology for managing transactions and communicate to society about their efforts toward sustainability.

5.2 Case study B

The case under study was conducted in Phase III of the PhD research approach, and it aimed to provide findings to support the answer to the third research question that this PhD research work is concerning: **RQ3 -** *What are the implications of blockchain technology adoption in the supply chain structure of an additive symbiotic network?*. Two scenarios are developed and analyzed: scenario I) "*as-is*" scenario – with the current map of the additive symbiotic network under study and scenario II) "*to-be*" scenario – a scenario drawn by the researcher considering the adoption of blockchain technology. These two scenarios aimed to understand how the adoption of blockchain technology implies in the relationships within an additive symbiotic network. Furthermore, the requirements for adopting blockchain technology in this additive symbiotic network, presented in section 3.2.1 and identified in the previous case study A, are also validated for the additive symbiotic network of the case under study.

5.2.1 Case study's description – B-PET's network

There are numerous possibilities to valorize waste through AM, as has been highlighted over the past chapters of this PhD thesis. AM technology can be one of the solutions to mitigate the discard of waste in landfills and respond to the increasing concerns of environmentalists, academics and local governments. According to Botello-Álvarez et al. (2018), when focusing on the municipality level, solid waste management is a complex problem, specifically in developing countries where it is typically inefficient due to the lack of proper financial and administrative structures, infrastructures, appropriate regulations, and human resources. Waste pickers' importance and relevance to the solid waste management problem have been studied mainly in Asian and Brazilian countries. For example, Botello-Álvarez et al. (2018) highlighted that Brazil is starting to recognize and formalize waste pickers' activities by creating urban cooperatives and public regulation of organized groups that perform selective collection, classification and commercialization of recyclables. Commonly in the large metropolis of the Global South, a few multinational corporations manage the collection and destination of urban garbage. However, since it is an expensive, time-consuming and bureaucratic process, only a few groups have achieved the formal status of a cooperative, and even a smaller group can have access to the official microfinance and funding opportunities (Gutberlet, 2012).

For this PhD research work, an exploratory case study was carried out on an additive symbiotic network in which AM technology is used to produce recycled filament used in 3D printers. In this case study, AM technology is provided by a 3D printing company that outsources production, provides start-up consulting services to manufacturers, provides commercial materials such as catalogues and branding, quality control criteria and procedures, and licenses the product's name. The company under study is named B-PET (https://bpetfilament.com/), with its global headquarters in Buenos Aires, Argentina and its European headquarters in Valencia, Spain. Within this network, it has the role of AM technology provider.

In 2016 different companies (including B-PET and the Instituto Nacional de Tecnología Industrial in Buenos Aires) had partner up to carry out a research which aimed to demonstrate that post-consumer recycled (PCR) plastics could be used in 3D printing to produce fully functional, mechanically advanced devices (Sher, 2016). B-PET developed the waste recycling process to incorporate it into AM equipment, allowing the production of the first 3D printing filament made 100% from PCR PET bottles (Figure 5-5). It is an engineering thermoplastic material mainly used for packaging purposes due to its excellent CO_2 and O_2 barrier and mechanical properties. In its amorphous phase, it's a colourless and crystal-clear material. B-PET effectively recycles PET waste streams into fully functional AM printed materials through fused filament fabrication technology.

Figure 5-5 Bottle PET Filament. Retrieved from: B-PET (2021)

The AM is seen as a more sustainable and distributed manufacturing, but this is inextricably linked to promoting the use of post-consumer plastics as consumable materials. The continuous development of methods for recycling post-consumer plastics (and thus, using them for creating PCR filament) is one key to the sustainable growth of the manufacturing industry (Sher, 2016). In this case study, PET bottles appear in urban solid waste streams and are gathered by urban waste collectors that are concentrated within the Buenos Aires Metropolitan Area. These waste collectors are precariously organized in cooperatives that produce bales with a selection of green, blue and "crystal"- clear bottles. According to Carenzo (2020), a vibrant creative practice takes place in waste pickers cooperatives, even though they are usually recognized as an alienated and unskilled population dedicated to collecting and sorting waste as a resort to make a living. These bales formed by the plastic waste streams are then dispatched to warehouses with a legal framework that can, in turn, sell them to one of the three authorized PET recyclers in Argentina that produce food-grade PET pellets from PET PCR waste, mainly through mechanical extrusion processes.

According to Gutberlet et al. (2017), the globalization of waste trade redefined resource relationships between the Global South and the Global North. Worldwide, countries and regions are linked and interconnected through resource and waste flows, creating a global system for resource recovery from waste. Thus, the circular economy concept is critical for countries in the Global South. As in most Global South cities, Buenos Aires has recognized innovations that aimed to foster inclusive recycling within the municipal waste management system, with professionals and technicians working in labs, workshops and contests to come up with affordable and straightforward solutions for collection logistics, building machinery or to handcraft goods from recovered recyclables (Carenzo, 2020).

However, Gutberlet et al. (2017) highlighted that cooperatives face several challenges related to purchase and contracting proceedings, with the need to fulfil a number of complex and time-consuming bureaucratic conditions that may jeopardize the purchase or maintenance of equipment, goods or services. Especially, difficulties exist for cooperatives in getting an invoice from the PCR bales that are sold to the National recyclers. Since the local cooperatives do not have the necessary means to get invoices for the waste streams they sell to ALEPK, there is a need for an intermediary entity. The local cooperatives, consequently, give to the intermediary information about the wastes that are being sent to the recycler, and in exchange, the intermediary offers money from selling the waste streams to the recycler. The intermediary passes information to the recycler about the waste streams and invoice data.

In this context, another challenge that arises relates to the availability of funds to invest in AM technologies, equipment and services. As highlighted in Gutberlet et al. (2017), contracting and purchasing are centralized by National Associations that control the funds and allow for little participation in the decision-making processes for the cooperatives. Still, cooperatives need adequate AM equipment and technologies to use the recycled filament made from the plastic waste streams. Hence, in this type of networks, typically, there is a need for a funding organization to obtain the funds to invest in AM equipment.

The funds can be made available through non-refundable subsidies that cover up to 70-80% of the value of the equipment and services. This type of funding is given by the Economy Ministry through the Industry department, for example, through *the Programa Federal de Fortelacimiento de la Reactivación Productiva (*https://www.boletinoficial.gob.ar/detalleAviso/primera/265497/20220704). Otherwise, the funding can also be made available by resorting to public funds. These public funding instruments have different requirements in order to make available the funds for a specific project, depending on its aim, scope, technology and materials used, and product design, among others. In Argentina, some of these public funding instruments include: *Aportes No Reembolsables Producción Más Limpia (ANR P+L)*, from Agencia Nacional de Promoción de La Investigación, el Desarrollo Tecnológio y La Innovacion (http://www.agencia.mincyt.gob.ar/frontend/agencia/instrumento/3) or Argentina.gob.Ar (https://www.argentina.gob.ar/produccion/financiamiento).

Still, the local cooperatives by themselves do not own the necessary means to get funds directly from the funding organizations. Consequently, there is a need to have an intermediary entity between the local cooperatives and the funding organizations. This intermediary asks the funders for money to invest in AM technology, services and equipment. In exchange, the funds are split between the intermediary entity and the local cooperatives.

The combination of adequate AM technology, equipment, and services with PET pellets makes it possible to produce filament for 3D printers. Typically, cooperatives buy raw materials (filament to produce AM products) from B-PET certified suppliers and sell final products to individuals or corporate consumers, such as schools or other 3D printing services companies. B-PET provides all technical know-how during the production line setup and quality control processes. B-PET also provides marketing support with Technical Data Sheets, Safety Data Sheets, and other commercial materials, namely the brand’s logo, name and sales channels. B-PET will continue developing new products through Research & Development and help build the networks within local communities worldwide.

Hence, this case study presents us with an additive symbiotic network supporting the valorization of PCR waste streams (i.e., PET bottles). The additive symbiotic network itself was considered to be the unit of analysis.

Table 5-4 provides an overview of the eleven stakeholders that comprise the case study. Eight entities are enrolled in the additive symbiotic network, namely: i) INTI – the National Institute of Industrial Technology – an institute that conducts scientific research and technical tests; ii) Enye Technologies – an innovation hub that created B-PET; iii) B-PET – company that produces and sell AM technology and services; iv) Funding entity – public funding to invest in 3D equipment and services; v) Intermediary entity – a consulting company that helps to get the funds from the public funding; vi) Cooperative Correcaminos – local cooperative that collects, separates and manages waste and that produces the recycled filament for 3D printers from the PCR PET pellets; vii) ANMAT – National Agency that approves companies to produce good grade PET pellets from PCR waste streams; viii) ALPEK – one of Argentina's PET recyclers for food-grade applications.

Three additional groups of stakeholders are considered despite they do not represent any specific entity: i) 3D printing services – multiple companies that use or sell AM technology and equipment; ii) Final consumers – multiple companies or individual consumers that aim to use AM printed products and iii) Prosumers – they represent the individuals (or organizations) that buy the recycled filament from the Cooperative and use it to produce AM products for their own needs.

Table 5-4 Stakeholders' description for case study B

Stakeholders	Description	Activity
INTI	National Institute of Industrial Technology in Argentina	Responsible for the development of industrial technology. Implements regulations and identifies product quality in industry and commerce. Promotes partnerships and local development and is responsible for public technology.
Enye Technologies	Design, technology and ideation company	Digital agency whose primary focus is building products based on people's needs. Creates and funds start-ups and spin-offs.
B-PET	Company that sells AM technologies and services	AM technologies and services

Table 5-4 Stakeholders' description for case study B (cont).

Stakeholders	Description	Activity
Funding entity	Public funding	Gives funds to invest in AM equipment and services
Intermediary	Consulting group	Helps to get the public funding
Cooperative Correcaminos	Local cooperative in Argentina that collects and recycles solid and inorganic residues such as metals, plastics, and paper	Local cooperative that collects, separates and manages waste and production of recycled filament for 3D printing
ANMAT	National Administration of Medicines, Food and Medical Technology in Argentina that assures that all health products are safe and of quality	Agency that approves companies to produce food-grade PET pellets from post-consumer waste streams
ALPEK (formally ECOPEK)	A global integrated polyester-based business unit, leader in the production of PET resins and PET recycling	Recycler company that transforms PET waste streams into PET pellets or flakes
Prosumers	Individuals	Individuals that use the recycled filament and AM equipment to produce products according to their needs
3D Printing Services Companies	Multiple companies that use or sell AM technology and equipment	Companies that use the recycled filament for personalized and customized products and services
Final consumers	Multiple companies or individual consumers	Consumers that aim to buy and use 3D printed products

5.2.2 Data collection

Considering the aim of this case study which was to understand the implications of adopting blockchain technology in the supply chain structure of an additive symbiotic network, to carry out this case study, two research stages were considered:

- Stage 1) "*as-is*" scenario I represents the current map of the additive symbiotic network. In this research phase, data regarding the network's stakeholders and resources exchanged among them was collected to create a value flow matrix to characterize the main flows and stakeholders of an additive symbiotic network (before the adoption of blockchain technology). This research phase intends to characterize the flows exchanged among stakeholders in an additive symbiotic network before adopting blockchain technology.

- Stage 2) "*to-be*" scenario II – this scenario was drawn considering the adoption of blockchain technology. It is a conceptual scenario developed by the researcher. The requirements for adopting blockchain technology highlighted in sub-chapter 3.2.1 are validated in this scenario. At this phase, data regarding the potential applications to use blockchain technology within the supply chain of an additive symbiotic network were collected. Additionally, data relating to the stakeholders and flows exchanged in the network was collected to create a new value flow matrix compared with the previous scenario I. The aim was to characterize the flows exchanged among stakeholders in the network after adopting blockchain technology.

For this case study, primary and secondary data were collected using different sources and methods. The primary data collection (Table 5-5) was performed through unstructured interviewers and questionnaires with an expert belonging to the focal organization of the network. The expert corresponded to a technical advisor with more than 15 years of experience that was involved in the team that created the first prototype of filament made from recycled post-consumer PET bottles.

Table 5-5 Primary data collection for case study B

Research stage	Objective	Data collection
Stage 1 "*as-is*" scenario	• Characterization of the case study • Identification of resources exchanged and stakeholders • Identification of the focal organization	• 2 Unstructured interviews • Questionnaire D.1 (Appendix D) • Observations "*in-loco*"
	• Identification and quantification of value flows	• 4 Unstructured interviews • Questionnaire D.2 • Additive symbiotic network – mapping and quantifying the value flows
Stage 2 "*to-be"* scenario"	• Identification of several applications of the blockchain technology within the additive symbiotic network	2 Unstructured interviews
	• Identification and quantification of value flows after blockchain technology	• Questionnaire D.3 (Appendix D)

The interviews aimed to collect data for both research phases regarding the additive symbiotic network, its stakeholders, and resources exchanged and to discuss and validate the study's main conclusions. In addition to the primary data collection, secondary data from the website news of B-PET (https://bpetfilament.com) was collected

Questionnaire D.1 was developed in the first research phase to understand the main resources exchanged and the main stakeholders in the network. After, Questionnaire D.2 was created to quantify the value flows within the network. Questionnaire D.3 was developed in the second research phase to understand the changes that could occur in quantifying each value flow after adopting blockchain technology. The three questionnaires are made available in Appendix E.

5.2.3 Data analysis

Similarly to the data analysis of case study A, to characterize the main flows and stakeholders in the additive symbiotic network of case study B, the methodology from Ferreira et al. (2019) was used. Within this case study, the following sub-sections describe and map the scenarios under study: scenario I - the current status of the network "*as-is*" and scenario II – "*to-be*" considering the adoption of blockchain technology.

5.2.3.1 Scenario I – "As-is"

1. **Identification of the stakeholders in the network**

The first step of the methodology to characterize an additive symbiotic network is to identify the focal organization in the network and its main stakeholders. In this case study, the B-PET company was responsible for producing and making available the AM technology necessary to incorporate PCR waste streams into filament for 3D printing. B-PET was responsible for providing the means to conduct all the research, studies, and tests for developing the bottles' PET filament. Thus, B-PET was considered in this study as the focal organization.

Through Questionnaire D.1 and unstructured interviews with the focal organization, it was possible to identify the different stakeholders of the network and their contribution to the symbiosis process.

Thus, the indirect partners for this case study are:

- **Enyetech** – the company is an innovation hub that first came up with the concept of using waste streams to produce filament for 3D printing. The company has also patented this process. After that, they created B- PET LLC, an independent spin-off company, to develop this business.
- **INTI** - INTI conducted the preliminary product development and validation. The company Enye Technologies has paid for several scientific research and technical tests and reports provided by INTI to demonstrate the feasibility of using PET pellets from PCR waste streams to produce filament for 3D printing.
- **ANMAT** - Currently, only companies with the national agency ANMAT's approval are capable of producing food-grade PET pellets from the PCR waste stream. Therefore, the approval of these entities is critical in this process.
- **Funding** –public funding is a way for the local cooperatives to get funds to invest in AM equipment and services through the help of an intermediary stakeholder. Public funding gives funding to both local cooperatives and the intermediary.

Additionally, as direct partners, it was considered:

- **Cooperative Correcaminos** – a local cooperative with two warehouses where they collect, separate and manage waste from different materials. The local cooperative is responsible for collecting and gathering waste streams and selling them in bales to PET recyclers in Argentina. In return, it receives the PET pellets or flakes ready to be used in the 3D printers to produce filament. Currently, this Cooperative is showing interest in acquiring a licence from B-PET LLC to manufacture B-PET filament products that they can use in two types of ways: As **Prosumers** - the cooperative sells the recycled filament to individuals or organizations (e.g., for schools) that use it to produce AM products. Or, to **3D printing services companies** – the cooperative sells the service to the market, which aims to satisfy the End consumers' needs.
- **ALPEK** - to effectively recycled PET to be used in AM, it is necessary that PET bottles from post-consumer streams are presented in the form of flakes or pellets. ALPEK is a global polyester producer and recycler and is one of Argentina's approved PET recyclers for food-grade applications. Within this additive symbiotic network, this company is responsible for selling PET pellets or flakes to the local cooperatives.
- **Intermediary** – considering that the cooperative Correcaminos has already developed a long-term relationship with ALPEK, they do not need an intermediary entity. Thus, for this symbiotic network, the Intermediary stakeholder is only responsible for supporting the Cooperative in obtaining the funds to invest in AM technology and equipment.

2. Identification of value flows

The next step of the methodology is to identify the value flows of the network. In Figure 5-6, the direct and indirect value flows (exchanged between the direct and indirect partners, respectively) are represented with filled and dashed arrows. For assessing each of the value flows within this additive symbiotic network, part I from Questionnaire D.2 and unstructured interviews with the expert from the focal organization were used.

In scenario I, the eleven main value flows presented in Figure 5-6 were identified within this network. The direct flows are represented with filled dashes, and the indirect flows are represented with arrowed dashes. Thus, for scenario I, direct flows were identified as follows:

- **Direct flow 1** – INTI was responsible for conducting the necessary research, tests, and reports to study the feasibility of using PCR PET pellets to produce the recycled filament in 3D printers.
- **Direct flow 2** – The focal organization, B-PET, receives funding from Enyetech to make investments and develop projects since B-PET is an Enyetech spin-off company.
- **Direct flow 3** – It is required by law to have approval from ANMAT for a company to sell food-grade PCR PET pellets. ALPEK is one of three recyclers' entities in Argentina with the ANMAT's necessary approval.
- **Direct flow 4**– In this additive symbiotic network, there is a need to have an Intermediary entity responsible for obtaining funds for the local Cooperative to invest in AM technologies and services. This Intermediary entity creates a funding network that helps the Cooperative develop their businesses.
- **Direct flow 5** – After receiving the request from the Cooperative to create a funding network, the Intermediary proceeds to a project presentation for the funding entity.
- **Direct flow 6** – The focal organization provides the local Cooperative with the AM technology and essential consulting services to produce AM consumables.
- **Direct flow 7** – This flow is composed of two separate flows:
    - **Direct flow 7a** – After collecting the bales of PCR PET bottles, the local Cooperative sends them to ALEPK to be converted into PET pellets or flakes.

- Direct flow 7b – Since converting the waste streams into PET pellets or flakes requires additional processes to capture value from such waste streams, the local Cooperative additionally sends money to ALPEK.

- Direct flow 8 – After producing the recycled filament, the Cooperative can use it for their own activities or sell it to individuals (prosumers).
- Direct flow 9 – The Cooperative can similarly sell the recycled filament to 3D printing services companies.
- Direct flow 10 – After receiving the recycled filament, the 3D Printing Services companies use it to produce customised products/services for their Customers.

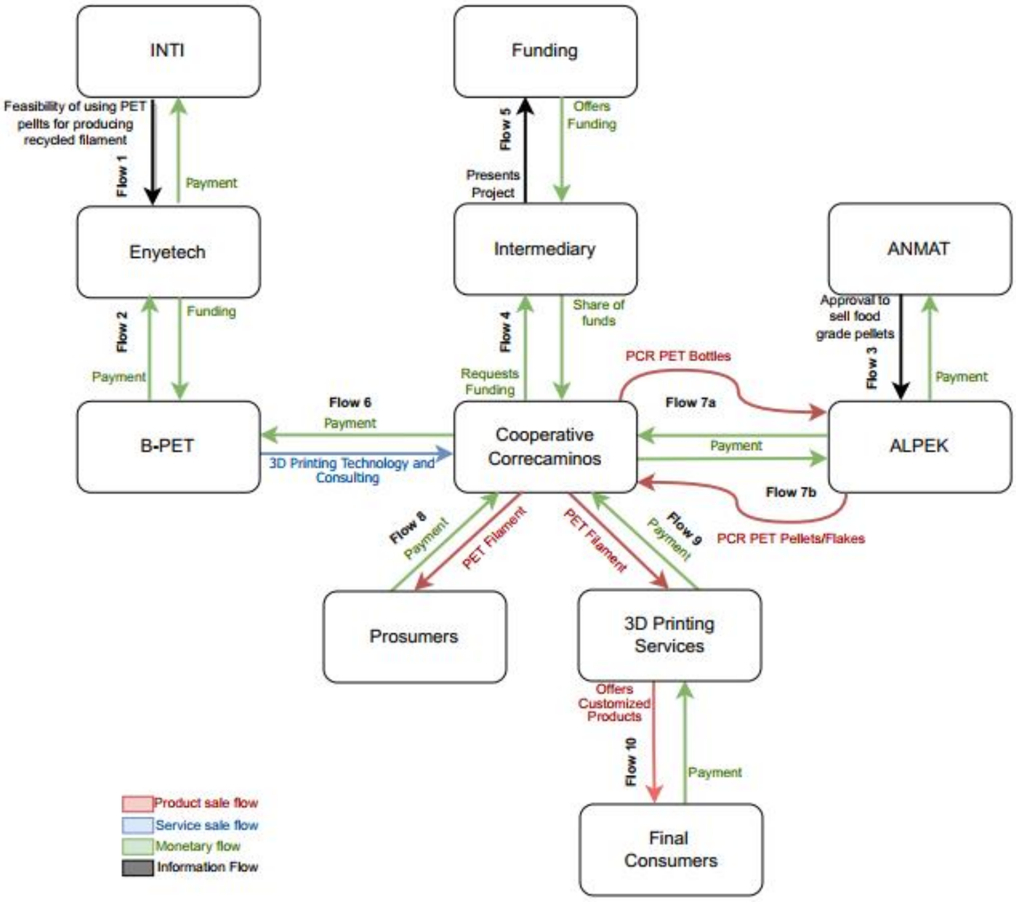


Figure 5-6 Identification of the value flows exchanged between the stakeholders of the additive symbiotic network from case study B in scenario I

Intrinsic to all the direct value flows are the reciprocal flows that were identified as follows:

- **Reciprocal flow 1** – The Enyetech company gives to INTI monetary support so they can develop their research around the production of recycled filament from the plastic waste streams.
- **Reciprocal flow 2** - Considering that B-PET main’s equity belongs to Enyetech, Enyetech receives money from B-PET's investments.
- **Reciprocal flow 3** - In exchange for the approval to sell food-grade PCR PET pellets, ALPEK must pay a fee to ANMAT.
- **Reciprocal flow 4** - In exchange for creating a funding network, the Cooperative shares the funds with the Intermediary entity that helps them achieve the funding networks.
- **Reciprocal flow 5** - After evaluating the projects presented by the Intermediary entities, the funds are made available by the Funding stakeholder and delivered to each stakeholder (Intermediary and the Cooperative).
- **Reciprocal flow 6** - A licence fee is paid from the cooperative to the focal organization, B-PET, in exchange for the AM technologies and services.
- **Reciprocal flow 7a** - ALPEK gives money to the local Cooperative in exchange for the bales of PCR PET bottles.
- **Reciprocal flow 7b** - PCR PET pellets or flakes are given by ALPEK to the local Cooperative.
- **Reciprocal flow 8** – The Prosumers give money in exchange for the 3D printing filament that they will use to produce their own products through AM technology.
- **Reciprocal flow 9** – The 3D printing services companies give money to the local cooperative in exchange for the 3D printing filament.
- **Reciprocal flow 10** - The Final Consumers give money to the 3D Printing Services companies in exchange for customized products and services.

3. Quantification of value flows and value flow matrix

Primary data collected from part II of Questionnaire D.2 were used to quantify each value flow previously identified. The scores attributed to each value flow (both direct and reciprocal) are available in Appendix E. The value flow matrix that arises from the different aggregated scores (which are the result of quantifying the value flows) allows for characterizing the different flows exchanged among the stakeholders of the additive symbiotic network. The value flow matrix for case study B is depicted in Table 5-6.

This value flow matrix allows us to conclude about the power of the stakeholders involved in this symbiotic network for the first scenario. Different aggregated scores indicate that there is a power distribution among the stakeholders.

Table 5-6 Value flow matrix for the additive symbiotic network B in scenario I

To: / From:	INTI	Enyetech	B-PET	Funding	Intermediary	Coop. Correcaminos	ANMAT	ALPEK	Prosumers	3D Printing services	Final consumers
INTI		Flow 1 – direct Research & Development (0.51)									
Enyetech	**Flow 1 – reciprocal** Money (0.11)		Flow 2 – direct Funding (0.96)								
B-PET		**Flow 2 – reciprocal** Money (0.01)				Flow 6 – direct 3D printing technology and consulting services (0.96)					
Funding					**Flow 5 – reciprocal** Funding (0.76)						
Intermediary				Flow 5 – direct Project Presentation (0.32)		Flow 4 – direct Funding Network (0.18)					
Cooperativa Correcaminos			**Flow 6 – reciprocal** Money (licence fee) (0.65)		**Flow 4 – reciprocal** Share of funding (0.54)			Flows 7a and 7b – direct Bales of PCR PET bottles (0.96) and money (0.22)	Flow 8 – direct 3D printing filament (0.32)	Flow 9 – direct 3D printing filament (0.11)	

Table 5-6 Value flow matrix for the additive symbiotic network B in scenario I (cont.)

To: / From:	INTI	Enyetech	B-PET	Funding	Intermediary	Coop. Correcaminos	ANMAT	ALPEK	Prosumers	3D Printing services	Final consumers
ANMAT								Flow 3 – direct Approval to produce food-grade pellets (0.76)			
ALPEK						**Flows 7a and 7b – reciprocal** Money (0.96) and PCR PET pellets or flakes (0.32)	**Flow 3 – reciprocal** Money (0.22)				
Prosumers						**Flow 8 – reciprocal** Money (0.54)					
3D Printing Services						**Flow 9 – reciprocal** Money (0.96)					Flow 10 – direct Customized products & services (0.76)
Final consumers										**Flow 10 – reciprocal** Money (0.96)	

The value flows with the highest aggregated scores are exchanged between the stakeholders who hold the most power in the network. In the case of this specific additive symbiotic network, the stakeholders Enyetech, B-PET, Cooperative Correcaminos, ALPEK, the 3D Printing Services companies and their Final Consumers are the stakeholders that hold the most power within the network.

5.2.3.2 Scenario II – "To-be"

To understand the possibilities of adopting blockchain technology within the supply chain of the additive symbiotic network, an unstructured interview was taken with the expert of the focal organization. The opportunities highlighted by the expert to use blockchain technology are:

- To identify players within the network and validate newcomers (new cooperatives, new prosumers or new organizations that use AM technology to valorise plastic waste) as a means to start introducing waste pickers to digital identities (all the information and a unique identifier is used for each waste picker to detect them and their devices) and the digital economy.
- The smart contracts that support the exchanges of resources (monetary, material and informational/knowledge) between stakeholders in a symbiotic network could help visualize indicators such as Life Cycle Assessment or CO_2 footprint. These incorruptible records could help build Final Consumers' confidence regarding sustainable practices, thus avoiding greenwashing and gaining sustainability certifications by independent entities. These independent entities may correspond to external consultants that support the access to obtaining funds (public or private). Examples of these may correspond to organizations such as TUV or Bureau Veritas.
- It could be used as a tool to certify the stakeholders' sustainability value to a supply chain through, for example, smart contracts that can deliver tokenized key indicators. Specifically, for the additive symbiotic network under study, the stakeholders such as the Local Cooperative, its Prosumers or the 3D printing services companies could guarantee their sustainable supply chain value through a key indicator presented in the smart contract for the exchanges where these stakeholders participate in.
- It could be used to automate the supply chain's contracts in the symbiotic network, supporting the different transactions within the network (monetary, resources, informational, etc.).

- End consumers and external stakeholders of the symbiotic network could have access, through blockchain technology, to sustainability indicators of the network, increasing transparency and value to society.

From the expert's point of view, even though there are different opportunities for potentially adopting blockchain technology in an additive symbiotic network context, there are several challenges that come along with them, such as:

- Manufacturing cultural challenges may arise. The additive symbiotic networks are connected with two main niches: the metallic and the polymeric. In what concerns to the metallic, AM is mainly associated with metallic and metallurgic industries and sometimes with aerospace and medical industries. The metallic and metallurgic industries are culturally connected to traditional manufacturing, but on the other hand, the aerospace and medical industries are more innovative and technological-oriented. This can generate a cultural shock between these industries, potentially changing resources among them and with others. Thus, when considering the adoption of innovative technologies, such as AM or blockchain technology, one of the main challenges might concern with how to insert these technologies into the value chain of the stakeholders involved in a symbiotic network in such a way that they can complement and agile the collaboration between different cultural industries. The same applies to the polymeric niche, especially for plastics.
- Training and educational/knowledge challenges. All the AM stakeholders recognize a gap regarding the need to learn how to work with AM. The aggregated value of adopting a new technology may, itself, be the main challenge. When companies adopt technologies such as the AM, they need to completely change their production process and equipment, their business models, and the design of their products, since AM focuses on customized production rather than massive production. Consequently, they need to educate and train their workers to effectively operate a new technology. For making the best use of new technologies, like AM and blockchain, all the stakeholders need to understand what the purpose is of using these technologies, how to implement them and their credibility (in the case of blockchain technology, stakeholders need to have confidence in an entity that is responsible for certificating and validating all the transactions in a network).

Considering that this case study intends to provide empirical insights for answering to the third research question of this PhD research work (**RQ3** - *What are the implications* *of blockchain technology adoption in the supply chain structure of an additive symbiotic network?*) and considering the conceptual model developed and presented in sub-chapter 3.2.2 (Figure 3-4) that serve as a base to understand the implications of adopting the blockchain technology in the supply chain structure of an additive symbiotic network, it expected that all the of identified applications of the blockchain technology in the supply chain of an additive symbiotic network have consequent implications within its supply chain structure.

Thus, scenario II was analyzed considering the four supply chain management areas identified by Cole et al. (2019), where the adoption of the blockchain technology is expected to bring value: i) to improve and automate contracts, ii) to reduce the need to develop trustworthy supply chain relationships, iii) to reduce the need of intermediaries and iv) to reduce the overall transactions costs. Scenario II was developed, considering scenario I as the baseline. A newer mapping of the symbiotic network with the adoption of blockchain technology was developed (Figure 5-6).

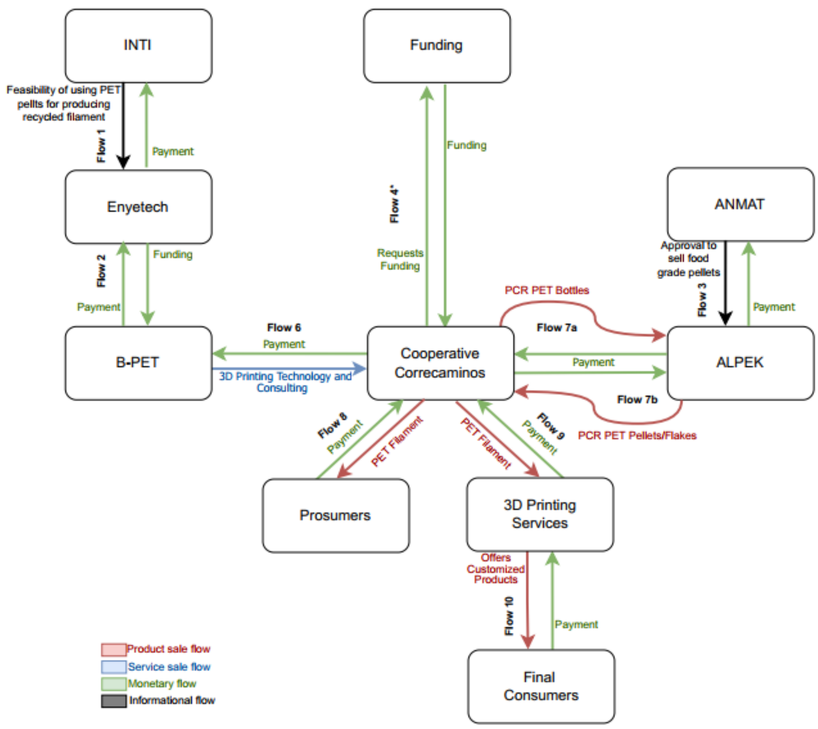


Figure 5-7 Identification of the value flows exchanged between the stakeholders of the additive symbiotic network from case study B in scenario II

In this new configuration, Flow 4* includes now the direct relationship between the Local Cooperative and the Funding stakeholders. In this flow, which replaces both flows 4 and 5 from the previous configuration, the Cooperative directly asks to the Funding stakeholder for the financial resources necessary to invest in AM technologies and equipment. In exchange, the Cooperative shares a fee from its profits with the Funding stakeholder. The remaining stakeholders and the flows (both direct and indirect) and the resources exchanged between them are kept similar to those identified and described in the scenario I. The expert from the focal organization validated this potential new scenario as one of the possibilities for blockchain technology adoption.

For mapping and analyzing the additive symbiotic network in this scenario II the same methodology used in subsection 5.2.3.1 was applied. The value flow matrix (Table 5-7) was updated and validated by the expert from the focal organization. Primary data from Questionnaire D.3 and an unstructured interview were used. The scores attributed to each value flow (both direct and reciprocal) are also available in Appendix E.

Table 5-7 Value flow matrix for the additive symbiotic network B in scenario II

From: \ To:	INTI	Enyetech	B-PET	Funding	Coop. Correcaminos	ANMAT	ALPEK	Prosumers	3D Printing services	Final consumers
INTI		Flow 1 – direct Research & Development (0.51)								
Enyetech	Flow 1 – reciprocal Money (0.11)		Flow 2 – direct Funding (0.96)							
B-PET		Flow 2 – reciprocal Money (0.01)			Flow 5 – direct 3D printing technology and consulting services (0.96)					
Funding					Flow 4 – Direct Funding (0.96)					
Cooperativa Correcaminos			Flow 6 – reciprocal Money (licence fee) (0.65)	Flow 4 – indirect Money (fee) (0.18)			Flows 7a and 7b – direct Bales of PCR PET bottles (0.96) and money (0.22)	Flow 8 – direct 3D printing filament (0.32)	Flow 9 – direct 3D printing filament (0.11)	
ANMAT							Flow 3 – direct Approval to produce food-grade pellets (0.76)			

Table 5-7 Value flow matrix for the additive symbiotic network B in scenario II (cont.)

To: / From:	INTI	Enyetech	B-PET	Funding	Coop. Correcaminos	ANMAT	ALPEK	Prosumers	3D Printing services	Final consumers
ALPEK					Flows 7a and 7b – reciprocal Money (0.96) and PCR PET pellets or flakes (0.32)	Flow 3 – reciprocal Money (0.22)				
Prosumers					Flow 8 – reciprocal Money (0.54)					
3D Printing Services					Flow 9 – reciprocal Money (0.96)					Flow 10 – direct Customized products & services (0.76)
Final consumers									Flow 10 – reciprocal Money (0.96)	

5.2.4 Results and discussion

From the value flow matrix created in scenario II (Table 5-7), it is possible to characterize the value flows and the stakeholders with the highest power after adopting blockchain technology in an additive symbiotic network. On the one hand, even though blockchain technology adoption enhances the relationship between the Cooperative (the manufacturing company) and the Funding stakeholders, it also increases the "urgency" and "dependence" scores used to quantify this value flow. The Cooperative has a higher urgency in receiving the necessary funds to invest in AM equipment and technologies and is also very dependent on the Funding stakeholder to receive those funds. However, the Funding stakeholder's "urgency" will depend on what is established on the smart contract (in terms of fees and long-term payments). Furthermore, the "dependence" of the Funding stakeholder is only related to the trust that the smart contracts will bring to the exchange with the Cooperative, which may lead the Funding stakeholder to incur in other similar networks (or similar projects). As already highlighted in Treiblmaier (2018), blockchain technology, specifically smart contracts, enables trusted information flows between companies that were disconnected before, altering the importance of inter-organizational relationships and thus, affecting some of the value flows and stakeholders that engage in an additive symbiotic network.

Table 5-7 shows that most of the stakeholders previously identified in scenario I as having the highest power are the same after adopting blockchain technology. In scenario II, with the elimination of the Intermediary stakeholder from the network, the Funding stakeholder gained more power and, thus, became one of the stakeholders that hold the most power within this additive symbiotic network. Flow 4* (Figure 5-7) now replaces both flows 4 and 5 from the scenario I (Figure 5-6), allowing the Cooperative to directly ask for funds from the Funding stakeholder.

Furthermore, in scenario II, the aggregated score for the value flows (both direct and reciprocal) increases between the stakeholders, Cooperative Correcaminos and Funding. This means that the power of these stakeholders rises within the network with the adoption of blockchain technology.

From the comparison of both scenarios developed for this case study and their respective value flow matrixes, and considering the different applications of blockchain technology in the supply chain of an additive symbiotic network, through a network theory lens, it is possible to conclude that the adoption of blockchain technology in an additive symbiotic network has implications within the supply chain structure of that network, namely:

- With the adoption of blockchain technology in an additive symbiotic network, there is a reduction in the number of stakeholders involved in the network, specially Intermediaries - which allows to validate part of the conceptual model developed to understand the implications of adopting blockchain technology in additive symbiotic setting and allows to corroborate some of the conclusions from Cole et al. (2019).
- There is a modification in the number of value flows within the network, corroborating Treiblmaier (2018). This modification exists because there is a reduction in the total number of value flows. If previously of adopting blockchain, there was a need to have two flows to achieve a specific objective; with the adoption of the technology, this can be done more directly, with fewer flows needed, and thus affecting the power distribution of the stakeholders within the network.

Furthermore, from this case study, it was also possible to validate the requirements to adopt the blockchain technology in such a setting, corroborating the findings from case study A. Namely, in the case B:

- Using a traditional database would not be possible since there is a need to track the transactions within the network, and, as a whole, the integrity must be guaranteed.
- There are multiple stakeholders with the power to update the database since the stakeholders involved play different roles in the symbiotic process, and there is a power distribution among them.
- The stakeholders do not know each other and, thus, do not have any cooperation or trust mechanisms between them.
- There is no interest in using a trusted third party since that would imply another organization outside the network to access the data.
- Public verifiability is not desired as the stakeholders might share sensitive and private information. However, the stakeholders involved in the network should have access to each other data (confidential system). So, the data shared among them do not need to be kept in private, as there is a need to keep a tracking record of the transactions occurring.
- Furthermore, the stakeholders' interests are also not aligned since they exchange different resources among them, thus affecting the power distribution in the network (i.e., stakeholders hold more power in the network than others) therefore, there is a need to have at least one stakeholder (the industrial symbiosis facilitator) to control changes in the database.

Through the development of this case study, it can be additionally emphasized that the adoption of blockchain technology in such settings is expected to have the following advantages:

- Elimination of intermediary entities, as there is no longer a need for a third party to be involved in the transaction within the networks.
- Keep available a tracking record of the resources (products and wastes) exchanged—namely, origin and details, especially in cases of the source of wastes comprising AM filaments.
- Transaction transparency reduces friction and infraction within the symbiotic network, as the records of each transaction cannot be changed at any point.
- Ease of collaboration, as all blockchain technologies are collaborative in nature, supporting the exchange of resources between the additive symbiotic stakeholders.
- Enhanced security of records, and thus, each transaction within the stakeholders is permanently recorded on the blockchain and made available to the stakeholders with the proper permission.
- Improved platform availability allows business to be conducted at any time, considering that in additive symbiotic networks, sometimes the stakeholders involved may be geographically distant from each other.
- Improved trust within the symbiotic network, supporting cooperation and trust mechanisms between the additive symbiotic stakeholders.
- Time-saving by using smart contracts since the contract terms are agreed upon and set between additive symbiotic stakeholders, and a third party does not have to verify them, thus, the whole process takes less time.

Despite these advantages, the adoption of such innovative technology in this type of network can also bring some challenges, such as:

- The complexity associated with introducing a novel technology, such as blockchain technology, in an emerging industry, such as additive manufacturing, already requires training staff or acquiring new IT infrastructures.
- The technology immaturity of blockchain when compared to other data storage technologies such as database servers.

6
CONCLUSIONS

This final chapter starts by presenting a review of the thesis and highlights how the different outputs contribute to achieving the thesis's aim. These results are discussed, and the main theoretical and managerial contributions are given. The chapter ends with suggestions for future research venues

6.1 Thesis overview

The AM industry reveals much potential for creating ISNs, the designated additive symbiotic networks. In these kinds of networks, wastes or by-products from other industries are used as material inputs for AM processes. However, given the digital nature of AM and considering challenges related to trust or tools to implement transactions, there is a need to find tools that enable additive symbiotic networks. Blockchain technology may be an enabler of such symbiotic networks, and its adoption within these settings may have implications for the supply chain of the additive symbiotic networks. Figure 6-1 provides a global overview of the thesis and its main outputs.

A systematic literature review highlighted the AM industry's potential to develop ISNs. From this literature review, a new definition is proposed: the additive symbiotic networks. Additive symbiotic networks are defined as ISNs in which wastes or by-products from different industries can be used as materials inputs for AM processes. These networks comprise different stakeholders that exchange resources between them, including manufacturing companies, AM technology providers, intermediaries, retailers, other product sellers and, sometimes, prosumers and customers.

In addition to this systematic literature review, the adoption of blockchain technology was explored within additive symbiotic networks. However, adopting such a disruptive technology as the blockchain should be carefully evaluated, especially considering the requirements of the additive symbiotic networks. Furthermore, it is expected that the adoption of such technology have implications within the supply chain of an additive symbiotic network. Specifically, in this PhD thesis, a focus is given on the supply chain structure.

Empirical data was collected through the case study method, which implied the development of two case studies (case studies A and B) comprising additive symbiotic networks involving companies that used AM processes to valorize plastic waste streams. This PhD research work intends to foster knowledge on a relatively new phenomenon and provide insights based on real-life situations that aim to provide a better understanding of the topics under study (the enablement of additive symbiotic networks with the adoption of blockchain technology). The additive symbiotic networks and the search for suitable tools to promote them contribute to the industrial symbiosis thematic.

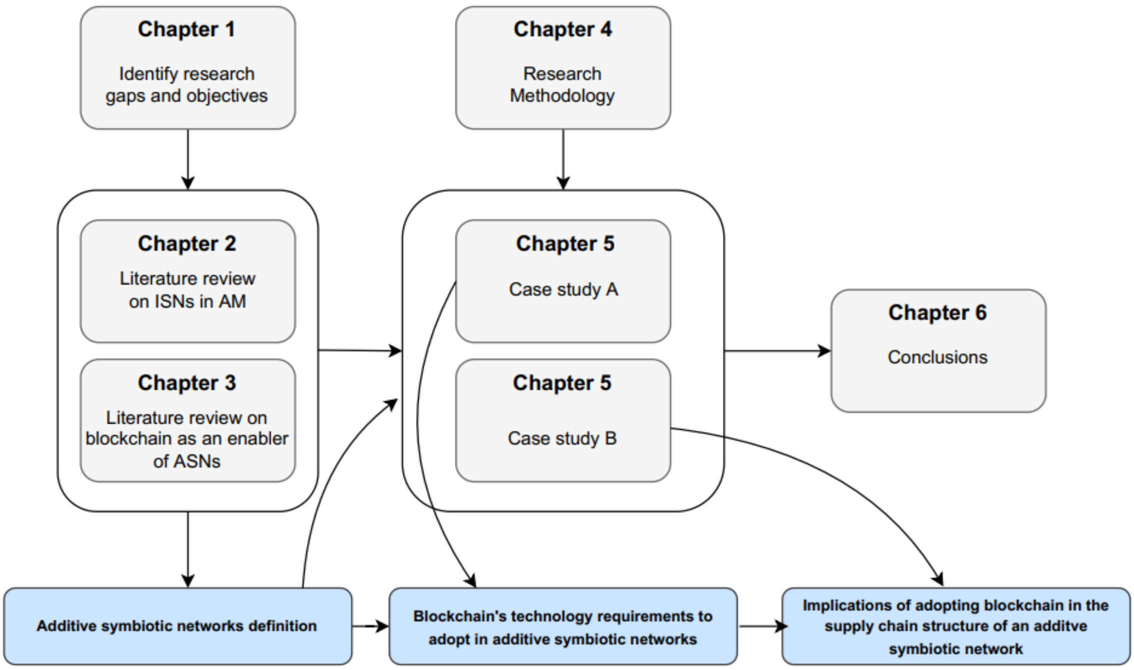


Figure 6-1 PhD Thesis's main outputs

Using empirical data from case study A, the requirements to adopt blockchain technology for implementing transactions in an additive symbiotic network are validated. After validating these, it is expected that adopting blockchain technology will enable the development of additive symbiotic networks. Thus, using empirical data from case study B, the adoption of blockchain technology is explored, namely its implications within the supply chain structure of an additive symbiotic network.

6.2 Main results

The systematic literature review revealed current circular economy relationships within the AM industry, highlighting that despite the potential of this industry to explore the concept of industrial symbiosis, the development of ISNs within this context is still in its infancy. Hence, giving rise to the designated additive symbiotic networks. This thesis explored the development of additive symbiotic networks by adopting blockchain technology. Thus, the results from the performed systematic literature review allow to answer to the first research question:

- **RQ 1** - *How to promote ISNs in the AM context?*

The literature review highlighted that from a total of 83 documents analyzed, 25 of them explored the possibility of having ISNs in the AM industry, namely through the exchange of wastes. From the analysis performed, it is possible to conclude that using plastic wastes from other industries as materials inputs for AM processes allows the creation and development of ISNs in the AM industry – the additive symbiotic networks.

Since this thesis aimed to understand the requirements to adopt blockchain technology as an enabler of these additive symbiotic networks, the findings from case studies A and B allow to answer to the second and third research questions:

- **RQ2** – *What are the requirements to make use of blockchain technology in an additive symbiotic network?*

To answer the second research question, the case study A is used to identify the main activities performed in an additive symbiotic network, which correspond to establishing transactions and monitoring and reporting. Considering these activities, case study A proves that there is space within the context of additive symbiotic networks to explore the adoption of blockchain technology. Furthermore, case study A concludes that blockchain technology fulfils a set of requirements to be adopted in an additive symbiotic network. These requirements correspond to: i) need of having a database that should allow to connect all the stakeholders and support the main activities involved an additive symbiotic network in the implementation phase of the industrial symbiosis creation process; ii) the need of having at least two of the stakeholders in the network updating the data in the database; iii) different levels of power within the symbiotic network lead to the inexistence of trust mechanisms between the stakeholders; and also iv) the inexistence of trust between the stakeholders and a third party; v) the data needs to be shared among the stakeholders so they can be able to monitor the status of each transaction and vi) the need to have a unique entity responsible for maintaining the network operationalized. Throughout the development of case study A, a permissioned blockchain was suggested to be adopted to support the development of the activities involved in implementing an additive symbiotic network, highlighting the role that blockchain technology may have as an enabler for promoting this type of symbiotic networks.

Even though such innovative technology as blockchain has proven to have many potential benefits for enhancing circular economy initiatives, and considering the results from case study A, especially for the development of additive symbiotic networks, adopting disruptive and innovative technologies may have several implications within the supply chain structure of those additive symbiotic networks. Thus, case study B was carried out, and its findings allow to answer to the third research question:

- RQ3 - *What are the implications of blockchain technology adoption in the supply chain structure of an additive symbiotic network?*

The requirements identified in case study A were also validated in case study B. From this, in case study B, two scenarios were analyzed. Scenario I analyzed the additive symbiotic network "*as-is*" in its current state. Scenario II was a conceptual scenario "*to-be*" developed by the researcher to understand the implications of the potential adoption of blockchain technology within the additive symbiotic network under study. Furthermore, results from the case study allowed to identify several applications of blockchain technology within the additive symbiotic network. These technology applications are expected to affect the supply chain structure of the symbiotic network under study.

The results from case study B allow to conclude that the implications of adopting blockchain technology in an additive symbiotic network are related to: i) a reduction in the number of Intermediary stakeholders involved in the network and ii) an adaption of the current value flows within the network. More precisely, for the case under study, in scenario II, which considered the adoption of blockchain technology, there is a removal of the Intermediary stakeholder. Thus, from this, an adaption of the value flows where the Intermediary stakeholder used to take part in, as new direct flows can replace indirect ones. The results also show an increase in the power of some stakeholders in the network (especially in the scenario that considers adopting blockchain technology), with new stakeholders potentially arising as holding the most power within the network and, thus, affecting the power distribution among the stakeholders involved.

By offering a tool that helps to deal with the challenges associated with the additive symbiotic networks, exploring its adoption and some of its implications in the supply chain of those networks, this PhD thesis intends to give insights into the development of the additive symbiotic networks, contributing for the efficient use of natural resources, promoting the collaboration between industries driven by a digital economy and reducing waste streams to achieve more sustainable production.

6.3 Theoretical and Managerial contributions

This PhD research work aims to promote the development of additive symbiotic networks to ensure more sustainable consumption habits by companies, protect resources that are considered critical and promote more sustainable use of the territorial ecosystem. Thus, considering the seventeen main sustainable development goals proposed by the United Nations in the Agenda 2030, this PhD research work can be connected and may contribute to achieving some of these goals. Namely, the sustainable goals number 9 and 12, "*Industry, Innovation and Infrastructure*" and "*Responsible consumption and production*", respectively. The additive symbiotic networks not only promote the share of resources among different industries intending to reduce resource consumption and the amount of waste generated but also allow for a more controlled and sustainable production and consumption of resources. Additionally, this PhD research work also explores the use of an innovative and disruptive technology, the blockchain, proposed as a tool to be adopted for enabling those additive symbiotic networks.

With the aim to contribute to the literature regarding the development of additive symbiotic networks, researchers, practitioners, and managers can benefit from this PhD thesis. In fact, this work allows to contribute to several aspects.

Theoretically, this PhD research work provides new insights into a phenomenon that is not totally understood yet and may serve as a basis for future replications within other settings. Moreover, this study extends the methodology developed for characterizing ISNs to the context of additive symbiotic networks. By extending its domain of applications, this PhD research work demonstrates the potential of the value network mapping for additive symbiotic networks and may be replicated to characterize other symbiotic networks. To promote the development of the additive symbiotic networks, this PhD research work explores the adoption of blockchain technology, extending its application domain to a new setting - the additive symbiotic networks and offering a tool for companies to engage in symbiotic relationships. This study also contributes to the literature by providing a conceptual model to understand some of the implications of adopting blockchain technology in the supply chain structure of an additive symbiotic network.

The development of this PhD thesis provided evidence that there are technical requirements associated with the development of additive symbiotic networks, such as: i) the need to have a waste material that can be used as a material input for an AM process and ii) the waste producers need to know about the use of the AM technology to incorporate waste from other industries. In recent years, blockchain has been regarded as one of the most disruptive technologies, triggering the introduction of new products and generating unique and distinctive business models. This study explores the adoption of blockchain technology in an additive symbiotic network setting along with the validation of the requirements to effectively support the adoption of such disruptive technology for this specific setting.

This PhD thesis provides management insights that can serve as decision-making guides for different stakeholders in the operations management process when considering the adoption of new technologies, such as AM or blockchain. The major aspects of these findings correspond to:

- There is a need to have proper mechanisms to support material flows and relationships and to manage trust imbalances between stakeholders in the network.
- Non-profit organizations and company managers can use blockchain technology to support the management of transactions and prove to society their efforts in pursuing sustainability.
- Since AM technology is moving to a higher degree of maturity and, thus, technology costs are decreasing, managers are encouraged to include this technology in their portfolio of green technologies.
- Using AM technology to valorize "waste" and residues in an ISN context may face challenges related to sharing the material characteristic among stakeholders. Since most AM processes require a high degree of purity and standardization of input materials, using a mixture of materials can imply additional operations for sorting and cleaning. Otherwise, stoppages in the printing process and defective products may occur.
- Blockchain technology can help trace wastes and by-products flows from origin until they are used as inputs in AM processes.
- Managers can take advantage of AM technology's reduced needs in terms of built infrastructure but also on the possibility of developing a decentralized additive

symbiotic network with the support of blockchain technology: the "waste" is transported through the symbiotic network, but the 3D printer is moved to the place where the "waste" is.

- By employing blockchain technology, additive symbiotic stakeholders can create and capture value, exchange information and trade, and organize themselves differently. Besides, information transparency is improved with blockchain technology, which tends to facilitate risk management at the corporate level (Chin et al., 2021).
- All parties use the proposed smart contract information throughout the additive symbiotic network. A smart contract can provide managers with trustworthy and timely information that assists them in making more educated, up-to-date decisions promptly. Using smart contracts, mediation, compromise, coordination, and record-keeping between additive symbiotic stakeholders can be automated, and managers can focus on more demanding and essential tasks.
- In this study, blockchain technology is applied to a real-world setting within the additive manufacturing industry to demonstrate future replication potential in the additive symbiotic environment.

Furthermore, from this PhD research work, it can be highlighted that even though the blockchain may be an enabler for promoting additive symbiotic networks, as interfaces between stakeholders that use the same blockchain technology is facilitated, adopting a new technology may bring new technological implications, namely:

- Effort is required only for the initial setup, as all the stakeholders need to use the same blockchain technology.
- There is a need for training staff to use the system.
- There is a need for the IT team to be trained to maintain the database.

6.4 Limitations and future research

Several shortcomings exist when concerning the research findings. The main limitations of this PhD research work are concerned with the development of only two case studies. Firstly, theoretical generalization is not possible using only two case studies that are not comparable with each other. In fact, in this PhD research work, a replication logic was not used, and so the results from each case study had different purposes. Another limitation is the focus on the AM industry and wastes and by-products exchanges. Industrial symbiosis relationships can be created within different contexts through the exchange of different resources; thus, the findings may not be universally applicable across different industries. Similarly, only implications within the supply chain structure of an additive symbiotic network were considered. Thus, different results can emerge from studying other implications of blockchain technology in other areas of the supply chain of an additive symbiotic network.

Since this PhD research work is an exploratory investigation, there is a need to proceed with further development of the additive symbiotic networks research. Even though this research explores the additive symbiotic network focusing on the incorporation of wastes or by-products, other actions can occur in an additive symbiotic network, such as the share of energy or infrastructures. Thus, future research may be carried out to explore other industrial symbiosis actions that can occur within the AM industry.

Several types of transaction costs can be identified when considering an industrial setting, such as: search costs (costs related to locating information about opportunities for exchanges), negotiation costs (costs associated with the negotiation of the terms of the exchanges) and enforcement costs (costs related to the enforcement of the contract). Thus, considering the usual high cost associated with the transactions, there is a need to find technically compatible streams and create and enforce a system of contracts outside the regular purchasing regime. With the adoption of blockchain technology, the stakeholders involved in the symbiotic networks might reduce the transaction costs associated with the network. Future research work may compare the transactions' costs of an additive symbiotic network before and after adopting blockchain technology. To complement and motivate the qualitative research regarding the use of the blockchain technology to enhance symbiotic networks, a quantitative analysis is suggested for future research work. This would include an environmental, social and economic impact assessment of the networks before and after considering the adoption of the blockchain technology.

Moreover, since trust is one of the most critical challenges in developing ISNs, and consequently, in additive symbiotic networks, adopting blockchain technology may potentially affect the relationships between the stakeholders involved in the network. Future research that addresses the impact of adopting blockchain technology in the inter-organizational relationships that form an additive symbiotic network will also improve the research to enhance the development of these networks.

The potential of blockchain technology to maintain and foster additive symbiotic networks in different contexts and countries is still in its infancy, with barely any recorded practical application yet. The first experiments in various blockchain applications need vital funding, which could yield remarkable benefits. This study promoted the adoption of blockchain technology to support the development of additive symbiotic networks. In this context, future research should include the development of a blockchain architecture based on smart contracts to enable an additive symbiotic network. From these, a need for a longitudinal study to monitor blockchain technology implementation in such a setting would also arise. Also, there are no existing regulations for blockchain technology, and as it rapidly develops, a gap is becoming apparent between the current legislation and the implications that it could have on additive symbiotic networks. Future studies could focus on a practical application of additive symbiotic networks, initially with few participants. Other studies can be made by addressing the widening gap between the lack of legislation and the rapid development of IT infrastructures based on blockchain technology.

When exploring the implications of adopting an innovative technology, as blockchain technology, in the supply chain of an additive symbiotic network, this PhD research work reveals other supply chain areas where the blockchain may have implications. Namely, it can be used as a tool to validate the degree of sustainability of an additive symbiotic exchange (for example, having a smart contract between two stakeholders delivering a key performance indicator for that exchange). This would enhance trust not only between the stakeholders participating in an additive symbiotic network, assuring they are certified stakeholders, but also with external stakeholders who desire to participate in those or other additive symbiotic networks. Thus, future research should relate to the blockchain as a tool to enhance trust within the stakeholders of an additive symbiotic network and how that implies the power distribution among the stakeholders involved.

With the aim to generalize more results and promote the development of additive symbiotic networks, future research should include more case studies regarding additive symbiotic networks that may also include the suggestion of other tools rather than blockchain technology to enhance such types of networks.

To conclude, it is expected that through industrial symbiosis strategies within the AM industry, taken together by different companies in a collaborative way, and through the adoption of innovative technologies to support the implementation of those strategies, there is an influence on the overall green supply chain management performance of the companies involved. In this sense, future research is suggested to be carried out to understand the implications of combining innovative technologies, such as the AM and the overall performance of the supply chain.

Bibliography

Abreu, M. C. S. de, & Ceglia, D. (2018). On the implementation of a circular economy: The role of institutional capacity-building through industrial symbiosis. *Resources, Conservation and Recycling*, *138*, 99–109. https://doi.org/10.1016/j.resconrec.2018.07.001

aclima. (2018). *Proyecto RecWood3D, la innovación y la economía circular al servicio de la impresión 3D – Aclima*. Aclima. Retrieved from: https://aclima.eus/proyecto-recwood3d-la-innovacion-y-la-economia-circular-al-servicio-de-la-impresion-3d/

Adaloudis, M., & Bonnin Roca, J. (2021). Sustainability tradeoffs in the adoption of 3D Concrete Printing in the construction industry. *Journal of Cleaner Production*, *307*, 127201. https://doi.org/10.1016/j.jclepro.2021.127201

Al Handawi, K., Andersson, P., Panarotto, M., Isaksson, O., & Kokkolaras, M. (2020). Scalable Set-Based Design Optimization and Remanufacturing for Meeting Changing Requirements. *Journal of Mechanical Design*, *143*(2). https://doi.org/10.1115/1.4047908

Albino, V., Fraccascia, L., & Giannoccaro, I. (2016). Exploring the role of contracts to support the emergence of self-organized industrial symbiosis networks: An agent-based simulation study. *Journal of Cleaner Production*, *112*, 4353–4366. https://doi.org/10.1016/j.jclepro.2015.06.070

Alexandre, A., Cruz Sanchez, F. A., Boudaoud, H., Camargo, M., & Pearce, J. M. (2020). Mechanical Properties of Direct Waste Printing of Polylactic Acid with Universal Pellets Extruder: Comparison to Fused Filament Fabrication on Open-Source Desktop Three-Dimensional Printers. *3D Printing and Additive Manufacturing*, *7*(5), 237–247. https://doi.org/10.1089/3dp.2019.0195

Alkhader, W., Alkaabi, N., Salah, K., Jayaraman, R., Arshad, J., & Omar, M. (2020). Blockchain-Based Traceability and Management for Additive Manufacturing. *IEEE Access*, *8*, 188363–188377. https://doi.org/10.1109/ACCESS.2020.3031536

Almonti, D., Mingione, E., Tagliaferri, V., & Ucciardello, N. (2022). Design and analysis of compound structures integrated with bio-based phase change materials and lattices obtained through additive manufacturing. *The International Journal of Advanced Manufacturing Technology*, *119*(1), 149–161. https://doi.org/10.1007/s00170-021-08110-2

Álvarez, R., & Ruiz-Puente, C. (2017). Development of the Tool SymbioSyS to Support the Transition Towards a Circular Economy Based on Industrial Symbiosis Strategies. *Waste and Biomass Valorization*, *8*(5), 1521–1530. https://doi.org/10.1007/s12649-016-9748-1

Andrew, J. J., & Dhakal, H. N. (2022). Sustainable biobased composites for advanced applications: Recent trends and future opportunities – A critical review. *Composites Part C: Open Access*, *7*, 100220. https://doi.org/10.1016/j.jcomc.2021.100220

Angioletti, C. M., Despeisse, M., & Rocca, R. (2017). Product Circularity Assessment Methodology. Em H. Lödding, R. Riedel, K.-D. Thoben, G. von Cieminski, & D. Kiritsis (Eds.), *Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing* (pp. 411–418). Springer International Publishing. https://doi.org/10.1007/978-3-319-66926-7_47

Angioletti, C. M., Sisca, F., Taisch, M., & Rocca, R. (2016). *Additive Manufacturing as an opportunity for supporting sustainability through implementation of circular economies*. In *21st Summer School Francesco Turco 2016* (pp. 25-25). AIDI-Italian Association of Industrial Operations Professors.

Ante, L. (2021). Smart contracts on the blockchain – A bibliometric analysis and review. *Telematics and Informatics*, *57*, 101519. https://doi.org/10.1016/j.tele.2020.101519

Arifin, N. A. M., Saman, M. Z. M., Sharif, S., & Ngadiman, N. H. A. (2022). Sustainability Implications of Additive Manufacturing. Em M. H. A. Hassan, Z. Ahmad (a) Manap, M. Z. Baharom, N. H. Johari, U. K. Jamaludin, M. H. Jalil, I. Mat Sahat, & M. N. Omar (Eds.), *Human-Centered Technology for a Better Tomorrow* (pp. 441–452). Springer. https://doi.org/10.1007/978-981-16-4115-2_35

Arrizubieta, J. I., Ukar, O., Ostolaza, M., & Mugica, A. (2020). Study of the Environmental Implications of Using Metal Powder in Additive Manufacturing and Its Handling. *Metals*, *10*(2), 261. https://doi.org/10.3390/met10020261

ASTM. (2016). *ISO/ASTM 52900:2015*. ISO. Retrieved from: https://www.astm.org/f3177-21.html

Atzori, M. (2017). Blockchain technology and decentralized governance: Is the state still necessary? *Journal of Governance and Regulation*, *6*(1), 45–62. https://doi.org/10.22495/jgr_v6_i1_p5

austintexas.gov. (2019). *City Announces [Re]Verse Pitch Finalists: Public Invited to Vote at Final [Re]Verse Pitch Competition | AustinTexas.gov*. Retrieved from: https://www.austintexas.gov/news/city-announces-reverse-pitch-finalists-public-invited-vote-final-reverse-pitch-competition

austintexas.gov. (2020). *Austin Resource Recovery | AustinTexas.gov*. Austin Resource Recovery. Retrieved from: https://www.austintexas.gov/department/austin-resource-recovery/about

Awaysheh, A., & Klassen, R. D. (2010). The impact of supply chain structure on the use of supplier socially responsible practices. *International Journal of Operations & Production Management*, *30*(12), 1246–1268. https://doi.org/10.1108/01443571011094253

Awuzie, B., & McDermott, P. (2017). An abductive approach to qualitative built environment research: A viable system methodological exposé. *Qualitative Research Journal*, *17*(4), 356–372. https://doi.org/10.1108/QRJ-08-2016-0048

Aziz, N. A., Adnan, N. A. A., Wahab, D. A., & Azman, A. H. (2021). Component design optimisation based on artificial intelligence in support of additive manufacturing repair and restoration: Current status and future outlook for remanufacturing. *Journal of Cleaner Production*, *296*, 126401. https://doi.org/10.1016/j.jclepro.2021.126401

Balouei Jamkhaneh, H., Shahin, R., & Tortorella, G. L. (2022). Analysis of Logistics 4.0 service quality and its sustainability enabler scenarios in emerging economy. *Cleaner Logistics and Supply Chain*, *4*, 100053. https://doi.org/10.1016/j.clscn.2022.100053

Barkane, A., Jurinovs, M., Briede, S., Platnieks, O., Onufrijevs, P., Zelca, Z., & Gaidukovs, S. (2022). Biobased Resin for Sustainable Stereolithography: 3D Printed Vegetable Oil Acrylate Reinforced with Ultra-Low Content of Nanocellulose for Fossil Resin Substitution. *3D Printing and Additive Manufacturing*. https://doi.org/10.1089/3dp.2021.0294

Barz, A., Buer, T., & Haasis, H.-D. (2016). A Study on the Effects of Additive Manufacturing on the Structure of Supply Networks. *IFAC-PapersOnLine*, *49*(2), 72–77. https://doi.org/10.1016/j.ifacol.2016.03.013

Bauman, Z. (2001). Consuming Life. *Journal of Consumer Culture*, *1*(1), 9–29. https://doi.org/10.1177/146954050100100102

Bergonzi, L., & Vettori, M. (2021). Mechanical properties comparison between new and recycled polyethylene terephthalate glycol obtained from fused deposition modelling waste. *Material Design & Processing Communications*, *3*(4), e250. https://doi.org/10.1002/mdp2.250

Bhatia, A., & Sehgal, A. K. (2021). Additive manufacturing materials, methods and applications: A review. *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2021.04.379

Bitting, S., Derme, T., Lee, J., Van Mele, T., Dillenburger, B., & Block, P. (2022). Challenges and Opportunities in Scaling up Architectural Applications of Mycelium-Based Materials with Digital Fabrication. *Biomimetics*, *7*(2), 44. https://doi.org/10.3390/biomimetics7020044

Blossey, G., Eisenhardt, J., & Hahn, G. (2019). Blockchain Technology in Supply Chain Management: An Application Perspective. *Hawaii International Conference on System Sciences 2019 (HICSS-52)*. Retrieved from: https://aisel.aisnet.org/hicss-52/os/impact_of_blockchain/6

Bluhm, D., Cook, W., Lee, T., & Mitchell, T. (2011). Qualitative Research in Management: A Decade of Progress. *Journal of Management Studies*, *48*, 1866–1891. https://doi.org/10.1111/j.1467-6486.2010.00972.x

Boons, F. A. A., & Baas, L. W. (1997). Types of industrial ecology: The problem of coordination. *Journal of Cleaner Production*, *5*, 1–2, 79-86. https://doi.org/10.1016/S0959-6526(97)00007-3

Botello-Álvarez, J. E., Rivas-García, P., Fausto-Castro, L., Estrada-Baltazar, A., & Gomez-Gonzalez, R. (2018). Informal collection, recycling and export of valuable waste as transcendent factor in the municipal solid waste management: A Latin-American reality. *Journal of Cleaner Production*, *182*, 485–495. https://doi.org/10.1016/j.jclepro.2018.02.065

B-PET. (2021). *B-Pet | Bottle PET Filament*. About B-PET. Retrieved from: https://bpetfilament.com/

Broome, M. E., Rodgers, B. L., & Knafl, K. A. (2000). *Concept Development in Nursing: Foundations, Techniques and Applications*. 2nd Edition. Philadelphia: Saunders Company.

Brousmiche, K.-L., Heno, T., Poulain, C., Dalmieres, A., & Hamida, E. (2018). *Digitizing, Securing and Sharing Vehicles Life-cycle over a Consortium Blockchain: Lessons Learned* (p. 5). https://doi.org/10.1109/NTMS.2018.8328733

Burmaoglu, S., Ozdemir Gungor, D., Kirbac, A., & Saritas, O. (2022). Future research avenues at the nexus of circular economy and digitalization. *International Journal of Productivity and Performance Management*, *ahead-of-print*(ahead-of-print). https://doi.org/10.1108/IJPPM-01-2021-0026

Byard, D. J., Woern, A. L., Oakley, R. B., Fiedler, M. J., Snabes, S. L., & Pearce, J. M. (2019). Green fab lab applications of large-area waste polymer-based additive manufacturing. *Additive Manufacturing*, *27*, 515–525. https://doi.org/10.1016/j.addma.2019.03.006

Cameron, B. G. (2007). *Value network modeling: A quantitative method for comparing benefit across exploration architectures* (Master Thesis, Massachusetts Institute of Technology). Retrieved from: https://dspace.mit.edu/handle/1721.1/40308

Caniato, F., Doran, D., Sousa, R., & Boer, H. (2018). Designing and developing OM research – from concept to publication. *International Journal of Operations & Production Management*, *38*(9), 1836–1856. https://doi.org/10.1108/IJOPM-01-2017-0038

Carenzo, S. (2020). Contesting informality through innovation "from below": Epistemic and political challenges in a waste pickers cooperative from Buenos Aires (Argentina). *Tapuya: Latin American Science, Technology and Society*, *3*(1), 441–471. https://doi.org/10.1080/25729861.2020.1788775

Carvalho, H. (2012). *Modelling resilience in supply chain* (Doctoral Dissertation, NOVA School of Science and Technology). Retrieved from: https://run.unl.pt/handle/10362/8949

Chalissery, D., Schönfeld, D., Walter, M., Shklyar, I., Andrae, H., Schwörer, C., Amann, T., Weisheit, L., & Pretsch, T. (2022). Highly Shrinkable Objects as Obtained from 4D Printing. *Macromolecular Materials and Engineering*, *307*(1), 2100619. https://doi.org/10.1002/mame.202100619

Chen, Y., & Bellavitis, C. (2020). Blockchain disruption and decentralized finance: The rise of decentralized business models. *Journal of Business Venturing Insights*, *13*, e00151. https://doi.org/10.1016/j.jbvi.2019.e00151

Chertow, M. R. (2000). Industrial Symbiosis: Literature and Taxonomy. *Annual Review of Energy and the Environment*, *25*(1), 313–337. https://doi.org/10.1146/annurev.energy.25.1.313

Chidepatil, A., Bindra, P., Kulkarni, D., Qazi, M., Kshirsagar, M., & Sankaran, K. (2020). From Trash to Cash: How Blockchain and Multi-Sensor-Driven Artificial Intelligence Can Transform Circular Economy of Plastic Waste? *Administrative Sciences*, *10*(2), 23. https://doi.org/10.3390/admsci10020023

Chin, T., Wang, W., Yang, M., Duan, Y., & Chen, Y. (2021). The moderating effect of managerial discretion on blockchain technology and the firms' innovation quality: Evidence from Chinese manufacturing firms. *International Journal of Production Economics*, *240*, 108219. https://doi.org/10.1016/j.ijpe.2021.108219

Chopra, S. S., & Khanna, V. (2014). Understanding resilience in industrial symbiosis networks: Insights from network analysis. *Journal of Environmental Management*, *141*, 86–94. https://doi.org/10.1016/j.jenvman.2013.12.038

Clemon, L. M., & Zohdi, T. I. (2018). On the tolerable limits of granulated recycled material additives to maintain structural integrity. *Construction and Building Materials*, *167*, 846–852. https://doi.org/10.1016/j.conbuildmat.2018.02.099

Cole, R., Stevenson, M., & Aitken, J. (2019). Blockchain technology: Implications for operations and supply chain management. *Supply Chain Management: An International Journal*, *24*(4), 469–483. https://doi.org/10.1108/SCM-09-2018-0309

Correia, E., Carvalho, H., Azevedo, S. G., & Govindan, K. (2017). Maturity Models in Supply Chain Sustainability: A Systematic Literature Review. *Sustainability*, *9*(1), 64. https://doi.org/10.3390/su9010064

Cress, A. K., Huynh, J., Anderson, E. H., O'neill, R., Schneider, Y., & Keleş, Ö. (2021). Effect of recycling on the mechanical behavior and structure of additively manufactured acrylonitrile butadiene styrene (ABS). *Journal of Cleaner Production*, *279*, 123689. https://doi.org/10.1016/j.jclepro.2020.123689

Creswell, J. W. (2003). *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. California, USA: SAGE Publications.

Cropanzano, R., Anthony, E. L., Daniels, S. R., & Hall, A. V. (2017). Social Exchange Theory: A Critical Review with Theoretical Remedies. *Academy of Management Annals*, *11*(1), 479–516. https://doi.org/10.5465/annals.2015.0099

Cropanzano, R., & Mitchell, M. S. (2016). Social Exchange Theory: An Interdisciplinary Review. *Journal of Management*. https://doi.org/10.1177/0149206305279602

Cruz Sanchez, F. A., Boudaoud, H., Camargo, M., & Pearce, J. M. (2020). Plastic recycling in additive manufacturing: A systematic literature review and opportunities for the circular economy. *Journal of Cleaner Production*, *264*, 121602. https://doi.org/10.1016/j.jclepro.2020.121602

Dal Fabbro, P., La Gala, A., Van De Steene, W., D'hooge, D. R., Lucchetta, G., Cardon, L., & Fiorio, R. (2020). Influence of machine type and consecutive closed-loop recycling on macroscopic properties for fused filament fabrication of acrylonitrile-butadiene-styrene parts. *Rapid Prototyping Journal*, *27*(2), 268–277. https://doi.org/10.1108/RPJ-03-2020-0060

Dalenogare, L. S., Benitez, G. B., Ayala, N. F., & Frank, A. G. (2018). The expected contribution of Industry 4.0 technologies for industrial performance. *International Journal of Production Economics*, *204*, 383–394. https://doi.org/10.1016/j.ijpe.2018.08.019

de León, A. S., Núñez-Gálvez, F., Moreno-Sánchez, D., Fernández-Delgado, N., & Molina, S. I. (2022). Polymer Composites with Cork Particles Functionalized by Surface Polymerization for Fused Deposition Modeling. *ACS Applied Polymer Materials*, *4*(2), 1225–1233. https://doi.org/10.1021/acsapm.1c01632

de Mattos Nascimento, D. L., Mury Nepomuceno, R., Caiado, R. G. G., Maqueira, J. M., Moyano-Fuentes, J., & Garza-Reyes, J. A. (2022). A sustainable circular 3D printing model for recycling metal scrap in the automotive industry. *Journal of Manufacturing Technology Management*, *33*(5), 876–892. https://doi.org/10.1108/JMTM-10-2021-0391

de Rubeis, T. (2022). 3D-Printed Blocks: Thermal Performance Analysis and Opportunities for Insulating Materials. *Sustainability*, *14*(3), 1077. https://doi.org/10.3390/su14031077

Demartini, M., Tonelli, F., & Govindan, K. (2022). An investigation into modelling approaches for industrial symbiosis: A literature review and research agenda. *Cleaner Logistics and Supply Chain*, *3*, 100020. https://doi.org/10.1016/j.clscn.2021.100020

Denyer, D., & Tranfield, D. (2009). Producing a systematic review. Em D. Buchanan & A. Bryman (Eds.), *The Sage Handbook of Organizational Research Methods* (pp. 671–689). Sage Publications Ltd.

DePalma, K., Walluk, M. R., Murtaugh, A., Hilton, J., McConky, S., & Hilton, B. (2020). Assessment of 3D printing using fused deposition modeling and selective laser sintering for a circular economy. *Journal of Cleaner Production*, *264*, 121567. https://doi.org/10.1016/j.jclepro.2020.121567

Dertinger, S. C., Gallup, N., Tanikella, N. G., Grasso, M., Vahid, S., Foot, P. J. S., & Pearce, J. M. (2020). Technical pathways for distributed recycling of polymer composites for distributed manufacturing: Windshield wiper blades. *Resources, Conservation and Recycling*, *157*, 104810. https://doi.org/10.1016/j.resconrec.2020.104810

Despeisse, M., Baumers, M., Brown, P., Charnley, F., Ford, S. J., Garmulewicz, A., Knowles, S., Minshall, T. H. W., Mortara, L., Reed-Tsochas, F. P., & Rowley, J. (2017). Unlocking value for a circular economy through 3D printing: A research agenda. *Technological Forecasting and Social Change*, *115*, 75–84. https://doi.org/10.1016/j.techfore.2016.09.021

Dev, N. K., Shankar, R., & Qaiser, F. H. (2020). Industry 4.0 and circular economy: Operational excellence for sustainable reverse supply chain performance. *Resources, Conservation and Recycling*, *153*, 104583. https://doi.org/10.1016/j.resconrec.2019.104583

Devarajan, B., Bhuvaneswari, V., Arulmurugan, B., Narayana, A. V. N. S. L., Priya, A. K., Kumar Abbaraju, V. D. N., Mukunthan, K. S., Sharma, A. K., Ting, S. S., & Masi, C. (2022). Hybrid Novel Additive Manufacturing for Sustainable Usage of Waste. *Journal of Nanomaterials*. https://doi.org/10.1155/2022/2697036

Di, L., & Yang, Y. (2022). Towards closed-loop material flow in additive manufacturing: Recyclability analysis of thermoplastic waste. *Journal of Cleaner Production*, *362*, 132427. https://doi.org/10.1016/j.jclepro.2022.132427

Domenech, T., Bleischwitz, R., Doranova, A., Panayotopoulos, D., & Roman, L. (2019). Mapping Industrial Symbiosis Development in Europe_ typologies of networks, characteristics, performance and contribution to the Circular Economy. *Resources, Conservation and Recycling*, *141*, 76–98. https://doi.org/10.1016/j.resconrec.2018.09.016

Domenech, T., & Davies, M. (2011). Structure and morphology of industrial symbiosis networks: The case of Kalundborg. *Procedia - Social and Behavioral Sciences*, *10*, 79–89. https://doi.org/10.1016/j.sbspro.2011.01.011

Donaldson, T., & Preston, L. E. (1995). The Stakeholder Theory of the Corporation: Concepts, Evidence, and Implications. *Academy of Management Review*, *20*(1), 65–91. https://doi.org/10.5465/amr.1995.9503271992

Durach, C. F., Blesik, T., von Düring, M., & Bick, M. (2021). Blockchain Applications in Supply Chain Transactions. *Journal of Business Logistics*, *42*(1), 7–24. https://doi.org/10.1111/jbl.12238

Eisenhardt, K. M. (1989). Building Theories from Case Study Research. *Academy of Management Review*, *14*(4), 532–550. https://doi.org/10.5465/amr.1989.4308385

Eisenhardt, K. M., & Graebner, M. E. (2007). Theory Building From Cases: Opportunities And Challenges. *Academy of Management Journal*, *50*(1), 25–32. https://doi.org/10.5465/amj.2007.24160888

Ellram, L., & Cooper, M. (2013). Supply Chain Management: It's All About the Journey, Not the Destination. *Journal of Supply Chain Management*, *50*. https://doi.org/10.1111/jscm.12043

Elsacker, E., Peeters, E., & De Laet, L. (2022). Large-scale robotic extrusion-based additive manufacturing with living mycelium materials. *Sustainable Futures*, *4*, 100085. https://doi.org/10.1016/j.sftr.2022.100085

Ertz, M., Sun, S., Boily, E., Kubiat, P., & Quenum, G. G. Y. (2022). How transitioning to Industry 4.0 promotes circular product lifetimes. *Industrial Marketing Management*, *101*, 125–140. https://doi.org/10.1016/j.indmarman.2021.11.014

Escursell, S., Llorach-Massana, P., & Roncero, M. B. (2021). Sustainability in e-commerce packaging: A review. *Journal of Cleaner Production*, *280*, 124314. https://doi.org/10.1016/j.jclepro.2020.124314

European Commission. (2020a). *Directive 2008/98/EC on waste (Waste Framework Directive)—Environment—European Commission.* Retrieved from: https://ec.europa.eu/environment/waste/framework/

European Commission. (2020b). E*nd-of-waste criteria—Environment—European Commission*. Waste Framework Directive. Retrieved from: https://ec.europa.eu/environment/waste/framework/end_of_waste.htm

Faludi, J., Baumers, M., Maskery, I., & Hague, R. (2017). Environmental Impacts of Selective Laser Melting: Do Printer, Powder, Or Power Dominate? *Journal of Industrial Ecology*, *21*(S1), S144–S156. https://doi.org/10.1111/jiec.12528

Fanta, G. B., Pretorius, L., & Nunes, B. (2021). Enabling circular economy in healthcare using industry 4.0 digital technologies. In *Proceedings of the 30th International Conference of the International Association for Management of Technology, IAMOT*. Cairo, Egypt, 1111–1123. https://doi.org/10.52202/060557-0085

VFavier, A., & Petit, A. (2022). Strategies for Reducing the Environmental Footprint of Additive Manufacturing via Sprayed Concrete. Em R. Buswell, A. Blanco, S. Cavalaro, & P. Kinnell (Eds.), *Third RILEM International Conference on Concrete and Digital Fabrication* (pp. 105–110). Springer International Publishing. https://doi.org/10.1007/978-3-031-06116-5_16

Feng, W. (2013). *Strategic management for large engineering projects: The stakeholder value network approach* (Doctoral Dissertation, Massachusetts Institute of Technology). Retrieved from: https://dspace.mit.edu/handle/1721.1/80983

Ferreira, I. A., Barreiros, M. S., & Carvalho, H. (2019). The industrial symbiosis network of the biomass fluidized bed boiler sand—Mapping its value network. *Resources, Conservation and Recycling*, *149*, 595–604. https://doi.org/10.1016/j.resconrec.2019.06.024

Ferreira, I. A., Godina, R., & Carvalho, H. (2021). Waste Valorization through Additive Manufacturing in an Industrial Symbiosis Setting. *Sustainability*, *13*(1), 234. https://doi.org/10.3390/su13010234

Ferreira, I. A., de Castro Fraga, M., Godina, R., Souto Barreiros, M., & Carvalho, H. (2019). A Proposed Index of the Implementation and Maturity of Circular Economy Practices—The Case of the Pulp and Paper Industries of Portugal and Spain. *Sustainability*, *11*(6), 1722. https://doi.org/10.3390/su11061722

Fico, D., Rizzo, D., De Carolis, V., Montagna, F., Palumbo, E., & Corcione, C. E. (2022). Development and characterization of sustainable PLA/Olive wood waste composites for rehabilitation applications using Fused Filament Fabrication (FFF). *Journal of Building Engineering*, *56*, 104673. https://doi.org/10.1016/j.jobe.2022.104673

Ford, S., & Despeisse, M. (2016). Additive manufacturing and sustainability: An exploratory study of the advantages and challenges. *Journal of Cleaner Production*, *137*, 1573–1587. https://doi.org/10.1016/j.jclepro.2016.04.150

Fraccascia, L., Yazdanpanah, V., van Capelleveen, G., & Yazan, D. M. (2021). Energy-based industrial symbiosis: A literature review for circular energy transition. *Environment, Development and Sustainability*, *23*(4), 4791–4825. https://doi.org/10.1007/s10668-020-00840-9

Freeman, R. E. (1984). *Strategic management: A stakeholder approach*. Bosto, USA: Pitman.

Freeman, R. E., Harrison, J. S., Wicks, A. C., Parmar, B. L., & Colle, S. de. (2010). *Stakeholder Theory: The State of the Art*. Cambridge University Press.

Freeman, R., & Mcvea, J. (2001). A Stakeholder Approach to Strategic Management. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.263511

Gadde, L. E., & Hakansson, H. (2001). *Supply Network Strategies*. Chichester, England: John Wiley & Sons.

Ganeriwalla, A., Casey, M., Shrikrishna, P., Bender, J. P., & Gstettner, S. (2018, março 16). *Does Your Supply Chain Need a Blockchain?* BCG Global. Retrieved from: https://www.bcg.com/publications/2018/does-your-supply-chain-need-blockchain

Ganter, N. V., Bode, B., Gembarski, P. C., & Lachmayer, R. (2021). *Method for upgrading a component within refurbishment*. *1*, 2057–2065. https://doi.org/10.1017/pds.2021.467

Ganter, N. V., Ehlers, T., Gembarski, P. C., & Lachmayer, R. (2021). *Additive refurbishment of a vibration-loaded structural component*. *1*, 345–354. https://doi.org/10.1017/pds.2021.35

Gatteschi, V., Lamberti, F., Demartini, C., Pranteda, C., & Santamaria, V. (2018). To Blockchain or Not to Blockchain: That Is the Question. *IT Professional*, *20*, 62–74. https://doi.org/10.1109/MITP.2018.021921652

Genovese, A., Acquaye, A. A., Figueroa, A., & Koh, S. C. L. (2017). Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications. *Omega*, *66*, 344–357. https://doi.org/10.1016/j.omega.2015.05.015

Ghimire, T., Joshi, A., Sen, S., Kapruan, C., Chadha, U., & Selvaraj, S. K. (2022). Blockchain in additive manufacturing processes: Recent trends & its future possibilities. *Materials Today: Proceedings*, *50*, 2170–2180. https://doi.org/10.1016/j.matpr.2021.09.444

Gill, P., Stewart, K., Treasure, E., & Chadwick, B. (2008). Methods of data collection in qualitative research: Interviews and focus groups. *British Dental Journal*, *204*(6), 291–295. https://doi.org/10.1038/bdj.2008.192

Giurco, D., Littleboy, A., Boyle, T., Fyfe, J., & White, S. (2014). Circular Economy: Questions for Responsible Minerals, Additive Manufacturing and Recycling of Metals. *Resources*, *3*(2), 432–453.

https://doi.org/10.3390/resources3020432

Golosova, J., & Romanovs, A. (2018). The Advantages and Disadvantages of the Blockchain Technology. *2018 IEEE 6th Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE)*, 1–6. https://doi.org/10.1109/AIEEE.2018.8592253

Gonçalves, R., Ferreira, I., Godina, R., Pinto, P., & Pinto, A. (2022). A Smart Contract Architecture to Enhance the Industrial Symbiosis Process Between the Pulp and Paper Companies—A Case Study. In J. Prieto, A. Partida, P. Leitão, & A. Pinto (Eds.), *Blockchain and Applications* (pp. 252–260). Springer International Publishing. https://doi.org/10.1007/978-3-030-86162-9_25

Gorkhali, A., Li, L., & Shrestha, A. (2020). Blockchain: A literature review. *Journal of Management Analytics*, *7*(3), 321–343. https://doi.org/10.1080/23270012.2020.1801529

Gouveia, J. R., Pinto, S. M., Campos, S., Matos, J. R., Sobral, J., Esteves, S., & Oliveira, L. (2022). Life Cycle Assessment and Cost Analysis of Additive Manufacturing Repair Processes in the Mold Industry. *Sustainability*, *14*(4), 2105. https://doi.org/10.3390/su14042105

Grasso, A., Matarazzo, A., Gentile, M., Abramo, G., & Visco, A. (2021). Technological innovation applied to the production of customized padel rackets. *Procedia Environmental Science, Engineering and Management*, *8*(3), 651–656.

Guetterman, T. C., & Fetters, M. D. (2018). Two Methodological Approaches to the Integration of Mixed Methods and Case Study Designs: A Systematic Review. *American Behavioral Scientist*, *62*(7), 900–918. https://doi.org/10.1177/0002764218772641

Guo, N., & Leu, M. C. (2013). Additive manufacturing: Technology, applications and research needs. *Frontiers of Mechanical Engineering*, *8*(3), 215–243. https://doi.org/10.1007/s11465-013-0248-8

Guo, S., Shen, B., Choi, T.-M., & Jung, S. (2017). A review on supply chain contracts in reverse logistics: Supply chain structures and channel leaderships. *Journal of Cleaner Production*, *144*, 387–402. https://doi.org/10.1016/j.jclepro.2016.12.112

Gutberlet, J. (2012). Informal and Cooperative Recycling as a Poverty Eradication Strategy. *Geography Compass*, *6*(1), 19–34. https://doi.org/10.1111/j.1749-8198.2011.00468.x

Gutberlet, J., Carenzo, S., Kain, J.-H., & Mantovani Martiniano de Azevedo, A. (2017). Waste Picker Organizations and Their Contribution to the Circular Economy: Two Case Studies from a Global South Perspective. *Resources*, *6*(4), 52. https://doi.org/10.3390/resources6040052

Håkansson, A. (2013). Portal of Research Methods and Methodologies for Research Projects and Degree Projects. In Proceedings of the International Conference on Frontiers in Education: Computer Science and Computer Engineering FECS'13 / [ed] Hamid R. Arabnia Azita Bahrami Victor A. Clincy Leonidas Deligiannidis George Jandieri, Las Vegas USA: CSREA Press U.S.A , 2013, p. 67-73. 1-60132-243-7

Haleem, A., & Javaid, M. (2019). Additive Manufacturing Applications in Industry 4.0: A Review. *Journal of Industrial Integration and Management*, *04*. https://doi.org/10.1142/S2424862219300011

Halldorsson, A. (2002). *Third Party Logistics. A means to cont logistics resources and competencies* (Doctoral Dissertation, Samfundslitteratur., Ph.D.serie No. 2002-25)

Halldorsson, A., Kotzab, H., Mikkola, J. H., & Skjøtt-Larsen, T. (2007). Complementary theories to supply chain management. *Supply Chain Management: An International Journal*, *12*(4), 284–296. https://doi.org/10.1108/13598540710759808

Hastig, G. M., & Sodhi, M. S. (2020). Blockchain for Supply Chain Traceability: Business Requirements and Critical Success Factors. *Production and Operations Management*, *29*(4), 935–954. https://doi.org/10.1111/poms.13147

Häußler, M., Eck, M., Rothauer, D., & Mecking, S. (2021). Closed-loop recycling of polyethylene-like materials. *Nature*, *590*(7846), 423–427. https://doi.org/10.1038/s41586-020-03149-9

Hawlitschek, F., Notheisen, B., & Teubner, T. (2018). The limits of trust-free systems: A literature review on blockchain technology and trust in the sharing economy. *Electronic Commerce Research and Applications*, *29*, 50–63. https://doi.org/10.1016/j.elerap.2018.03.005

He, D., Kim, H. C., De Kleine, R., Soo, V. K., Kiziltas, A., Compston, P., & Doolan, M. (2022). Life cycle energy and greenhouse gas emissions implications of polyamide 12 recycling from selective laser sintering for an injection-molded automotive component. *Journal of Industrial Ecology*, *26*(4), 1378–1388. https://doi.org/10.1111/jiec.13277

Hein, A. M., Jankovic, M., Feng, W., Farel, R., Yune, J. H., & Yannou, B. (2017). Stakeholder power in industrial symbioses: A stakeholder value network approach. *Journal of Cleaner Production*, *148*, 923–933. https://doi.org/10.1016/j.jclepro.2017.01.136

Hennemann Hilario da Silva, T., & Sehnem, S. (2022). The circular economy and Industry 4.0: Synergies and challenges. *Revista de Gestão*, *29*(3), 300–313. https://doi.org/10.1108/REGE-07-2021-0121

Herczeg, G. (2016). *Supply Chain Management in Industrial Symbiosis Networks* (Doctoral Dissertation, Technical University of Denmkar - DTU Management Engineering). Retrieved from: https://backend.orbit.dtu.dk/ws/portalfiles/portal/125886128/Herczeg_PhD_thesis.pdf

Herczeg, G., Akkerman, R., & Hauschild, M. Z. (2018). Supply chain collaboration in industrial symbiosis networks. *Journal of Cleaner Production*, *171*, 1058–1067. https://doi.org/10.1016/j.jclepro.2017.10.046

Hettiarachchi, B. D., Brandenburg, M., & Seuring, S. (2022). Connecting additive manufacturing to circular economy implementation strategies: Links, contingencies and causal loops. *International Journal of Production Economics*, *246*, 108414. https://doi.org/10.1016/j.ijpe.2022.108414

HID Global. (2021a). *About HID Global*. HID Global. Retrieved from: https://www.hidglobal.com/about

HID Global. (2021b). *HID Global—Powering trusted identities for your business*. HID Global. Retrieved from: https://www.hidglobal.com/homepage-view

Holland, M., Nigischer, C., & Stjepandic, J. (2017). Copyright Protection in Additive Manufacturing with Blockchain Approach. *Transdisciplinary Engineering: A Paradigm Shift*, *5*, 914–921. https://doi.org/10.3233/978-1-61499-779-5-914

Irannezhad, E. (2020). The Architectural Design Requirements of a Blockchain-Based Port Community System. *Logistics*, *4*(4), 30. https://doi.org/10.3390/logistics4040030

Jafferson, J. M., & Chatterjee, D. (2021). A review on polymeric materials in additive manufacturing. *Materials Today: Proceedings*, *46*, 1349–1365. https://doi.org/10.1016/j.matpr.2021.02.485

Järvenpää, A.-M., Salminen, V., & Kantola, J. (2021). Industrial Symbiosis, Circular Economy and Industry 4.0 – A Case Study in Finland. *Management and Production Engineering Review*. https://doi.org/10.24425/mper.2021.139999

Jiao, W., & Boons, F. (2014). Toward a research agenda for policy intervention and facilitation to enhance industrial symbiosis based on a comprehensive literature review. *Journal of Cleaner Production*, *67*, 14–25. https://doi.org/10.1016/j.jclepro.2013.12.050

Kahkonen, A.-K. (2014). Conducting a Case Study in Supply Management. *Operations and Supply Chain Management: An International Journal*, *4*(1), 31–41. https://doi.org/10.31387/oscm090054

Kanda, W., Geissdoerfer, M., & Hjelm, O. (2021). From circular business models to circular business ecosystems. *Business Strategy and the Environment*, *30*(6), 2814–2829. https://doi.org/10.1002/bse.2895

Karlsson, C. (Ed.). (2016). *Research Methods for Operations Management* (2.ª ed.). London, England: Routledge.

Karuppiah, K., Sankaranarayanan, B., & Ali, S. M. (2021). A decision-aid model for evaluating challenges to blockchain adoption in supply chains. *International Journal of Logistics Research and Applications*, *0*(0), 1–22. https://doi.org/10.1080/13675567.2021.1947999

Kasthala, V. (2019). Blockchain key characteristics and conditions to use it as a solution. Retrieved from: https://medium.com/swlh/blockchain-characteristics-and-its-suitability-as-a-technical-solution-bd65fc2c1ad1

Kayikci, Y., Gozacan-Chase, N., Rejeb, A., & Mathiyazhagan, K. (2022). Critical success factors for implementing blockchain-based circular supply chain. *Business Strategy and the Environment*, *2022*. https://doi.org/10.1002/bse.3110

Kennedy, S., & Linnenluecke, M. K. (2022). Circular economy and resilience: A research agenda. *Business Strategy and the Environment*, *n/a*. https://doi.org/10.1002/bse.3004

Kennedy, Z. C., Stephenson, D. E., Christ, J. F., Pope, T. R., Arey, B. W., Barrett, C. A., & Warner, M. G. (2017). Enhanced anti-counterfeiting measures for additive manufacturing: Coupling lanthanide nanomaterial chemical signatures with blockchain technology. *Journal of Materials Chemistry C*, *5*(37), 9570–9578. https://doi.org/10.1039/C7TC03348F

Khan, F., & Ali, Y. (2022). Implementation of the circular supply chain management in the pharmaceutical industry. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-021-02007-6

Khan, S. N., Loukil, F., Ghedira-Guegan, C., Benkhelifa, E., & Bani-Hani, A. (2021). Blockchain smart contracts: Applications, challenges, and future trends. *Peer-to-Peer Networking and Applications*, *14*(5), 2901–2925. https://doi.org/10.1007/s12083-021-01127-0

Khorram Niaki, M., Nonino, F., Palombi, G., & Torabi, S. A. (2019). Economic sustainability of additive manufacturing: Contextual factors driving its performance in rapid prototyping. *Journal of Manufacturing Technology Management*, *30*(2), 353–365. https://doi.org/10.1108/JMTM-05-2018-0131

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Koens, T., Poll, E. (2018). What Blockchain Alternative Do You Need? In: Garcia-Alfaro, J., Herrera-Joancomartí, J., Livraga, G., Rios, R. (eds) Data Privacy Management, Cryptocurrencies and Blockchain Technology. DPM CBT 2018 2018. Lecture Notes in Computer Science (), vol 11025. Springer, Cham. https://doi.org/10.1007/978-3-030-00305-0_9

Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular Economy: The Concept and its Limitations. *Ecological Economics*, *143*, 37–46. https://doi.org/10.1016/j.ecolecon.2017.06.041

Kosmol, L., & Esswein, W. (2018). Capturing the Complexity of Industrial Symbiosis. Em H.-J. Bungartz, D. Kranzlmüller, V. Weinberg, J. Weismüller, & V. Wohlgemuth (Eds.), *Advances and New Trends in Environmental Informatics* (pp. 183–197). Springer International Publishing. https://doi.org/10.1007/978-3-319-99654-7_12

Kouhizadeh, M., Saberi, S., & Sarkis, J. (2021). Blockchain technology and the sustainable supply chain: Theoretically exploring adoption barriers. *International Journal of Production Economics*, *231*, 107831. https://doi.org/10.1016/j.ijpe.2020.107831

Kouhizadeh, M., & Sarkis, J. (2018). Blockchain Practices, Potentials, and Perspectives in Greening Supply Chains. *Sustainability*, *10*(10), 3652. https://doi.org/10.3390/su10103652

Kouhizadeh, M., Sarkis, J., & Zhu, Q. (2019). At the Nexus of Blockchain Technology, the Circular Economy, and Product Deletion. *Applied Sciences*, *9*(8), 1712. https://doi.org/10.3390/app9081712

Kouhizadeh, M., Zhu, Q., & Sarkis, J. (2020). Blockchain and the circular economy: Potential tensions and critical reflections from practice. *Production Planning & Control*, *31*(11–12), 950–966. https://doi.org/10.1080/09537287.2019.1695925

Kovács, G., & Spens, K. M. (2005). Abductive reasoning in logistics research. *International Journal of Physical Distribution & Logistics Management*, *35*(2), 132–144. https://doi.org/10.1108/09600030510590318

Kravchenko, M., Pigosso, D. C. A., & McAloone, T. C. (2020). Circular economy enabled by additive manufacturing: Potential opportunities and key sustainability aspects. *DS 101: Proceedings of NordDesign 2020, Lyngby, Denmark, 12th - 14th August 2020*, 1–14. https://doi.org/10.35199/NORDDESIGN2020.4

Kreiger, M., Anzalone, G. C., Mulder, M. L., Glover, A., & Pearce, J. M. (2013). Distributed Recycling of Post-Consumer Plastic Waste in Rural Areas. *MRS Online Proceedings Library (OPL)*, *1492*, 91–96. https://doi.org/10.1557/opl.2013.258

Kromoser, B., Reichenbach, S., Hellmayr, R., Myna, R., & Wimmer, R. (2022). Circular economy in wood construction – Additive manufacturing of fully recyclable walls made from renewables: Proof of concept and preliminary data. *Construction and Building Materials*, *344*, 128219. https://doi.org/10.1016/j.conbuildmat.2022.128219

Kummer, S., Herold, D. M., Dobrovnik, M., Mikl, J., & Schäfer, N. (2020). A Systematic Review of Blockchain Literature in Logistics and Supply Chain Management: Identifying Research Questions and Future Directions. *Future Internet*, *12*(3), 60. https://doi.org/10.3390/fi12030060

Kurpjuweit, S., Schmidt, C. G., Klöckner, M., & Wagner, S. M. (2019). Blockchain in Additive Manufacturing and its Impact on Supply Chains. *Journal of Business Logistics*, *42*(1), 46-70. https://doi.org/10.1111/jbl.12231

Kuzman, M. K., Kariz, M., Ayrilmis, N., Šernek, M., Žigon, J., & Xu, Q. (2019). Fire behaviour of 3D printed PLA and Wood/PLA composites. In R. Chobanova (Eds.), *Procedia - Digitalisation and circular economy: Foresty and Foresty based Industry Implications. 12th Woodema Annual International Scientific Conference,* Sofia, Bulgaria, *(*149–154).

Lagorio, A., Zenezini, G., Mangano, G., & Pinto, R. (2020). A systematic literature review of innovative technologies adopted in logistics management. *International Journal of Logistics Research and Applications*, *0*(0), 1–24. https://doi.org/10.1080/13675567.2020.1850661

Lahrour, Y., & Brissaud, D. (2018). A Technical Assessment of Product/Component Re-manufacturability for Additive Remanufacturing. *Procedia CIRP*, *69*, 142–147. https://doi.org/10.1016/j.procir.2017.11.105

Lambe, C. J., Wittmann, C. M., & Spekman, R. E. (2001). Social Exchange Theory and Research on Business-to-Business Relational Exchange. *Journal of Business-to-Business Marketing*, *8*(3), 1–36. https://doi.org/10.1300/J033v08n03_01

Laoutid, F., Lafqir, S., Toncheva, A., & Dubois, P. (2021). Valorization of Recycled Tire Rubber for 3D Printing of ABS- and TPO-Based Composites. *Materials*, *14*(19), 5889. https://doi.org/10.3390/ma14195889

Laskurain-Iturbe, I., Arana-Landín, G., Landeta-Manzano, B., & Uriarte-Gallastegi, N. (2021). Exploring the influence of industry 4.0 technologies on the circular economy. *Journal of Cleaner Production*, *321*, 128944. https://doi.org/10.1016/j.jclepro.2021.128944

Leigh, M., & Li, X. (2015). Industrial ecology, industrial symbiosis and supply chain environmental sustainability: A case study of a large UK distributor. *Journal of Cleaner Production*, *106*, 632–643. https://doi.org/10.1016/j.jclepro.2014.09.022

Leino, M., Pekkarinen, J., & Soukka, R. (2016). The Role of Laser Additive Manufacturing Methods of Metals in Repair, Refurbishment and Remanufacturing – Enabling Circular Economy. *Physics Procedia*, *83*, 752–760. https://doi.org/10.1016/j.phpro.2016.08.077

Li, Y., & Pinto, M. C. B. (2021). Analyzing the Critical Success Factors for Industrial Symbiosis—A Chinese Perspective. Em R. K. Phanden, K. Mathiyazhagan, R. Kumar, & J. Paulo Davim (Eds.), *Advances in Industrial and Production Engineering* (pp. 23–33). Springer. https://doi.org/10.1007/978-981-33-4320-7_3

Liu, C., Zhang, X., & Medda, F. (2021). Plastic credit: A consortium blockchain-based plastic recyclability system. *Waste Management*, *121*, 42–51. https://doi.org/10.1016/j.wasman.2020.11.045

Liu, Z., Ashton, W. S., Adams, M., Wang, Q., Cote, R. P., Walker, T. R., Sun, L., & Lowitt, P. (2022). Diversity in financing and implementation pathways for industrial symbiosis across the globe. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-021-02086-5

Logan, M. S. (2000). Using Agency Theory to Design Successful Outsourcing Relationships. *The International Journal of Logistics Management*, *11*(2), 21–32. https://doi.org/10.1108/09574090010806137

Madsen, J. K., Boisen, N., Nielsen, L. U., & Tackmann, L. H. (2015). Industrial Symbiosis Exchanges: Developing a Guideline to Companies. *Waste and Biomass Valorization*, *6*(5), 855–864. https://doi.org/10.1007/s12649-015-9417-9

Makridakis, S., & Christodoulou, K. (2019). Blockchain: Current Challenges and Future Prospects/Applications. *Future Internet*, *11*(12), 258. https://doi.org/10.3390/fi11120258

Maldonado-García, B., Pal, A. K., Misra, M., Gregori, S., & Mohanty, A. K. (2021). Sustainable 3D printed composites from recycled ocean plastics and pyrolyzed soy-hulls: Optimization of printing parameters, performance studies and prototypes development. *Composites Part C: Open Access*, *6*, 100197. https://doi.org/10.1016/j.jcomc.2021.100197

Mandolla, C., Petruzzelli, A. M., Percoco, G., & Urbinati, A. (2019). Building a digital twin for additive manufacturing through the exploitation of blockchain: A case analysis of the aircraft industry. *Computers in Industry*, *109*, 134–152. https://doi.org/10.1016/j.compind.2019.04.011

Maranesi, C., & De Giovanni, P. (2020). Modern Circular Economy: Corporate Strategy, Supply Chain, and Industrial Symbiosis. *Sustainability*, *12*(22), 9383. https://doi.org/10.3390/su12229383

Marshall, G. (2005). The purpose, design and administration of a questionnaire for data collection. *Radiography*, *11*(2), 131–136. https://doi.org/10.1016/j.radi.2004.09.002

Matos, F., Godina, R., Espadinha-Cruz, P., & Matos, M. (2021). *Additive Manufacturing Technology: Designing New Business Models*. https://doi.org/10.34190/MLG.21.087

Matos, F., & Jacinto, C. (2018). Additive manufacturing technology: Mapping social impacts. *Journal of Manufacturing Technology Management*, *30*(1), 70–97. https://doi.org/10.1108/JMTM-12-2017-0263

McDonald, S. (2016). 3D Printing: a future collapse-compliant means of production. *In Proceedings of the Second Workshop on Computing within Limits (LIMITS '16).* Association for Computing Machinery, New York, NY, USA, Article 4, 1–6. https://doi.org/10.1145/2926676.2926680

Mentzer, J. T., DeWitt, W., Keebler, J. S., Min, S., Nix, N. W., Smith, C. D., & Zacharia, Z. G. (2001). Defining Supply Chain Management. *Journal of Business Logistics*, *22*(2), 1–25. https://doi.org/10.1002/j.2158-1592.2001.tb00001.x

Meredith, J. (1993). Theory Building through Conceptual Methods. *International Journal of Operations & Production Management*, *13*(5), 3–11. https://doi.org/10.1108/01443579310028120

Meyer, T. K., Tanikella, N. G., Reich, M. J., & Pearce, J. M. (2020). Potential of distributed recycling from hybrid manufacturing of 3-D printing and injection molding of stamp sand and acrylonitrile styrene acrylate waste composite. *Sustainable Materials and Technologies*, *25*, e00169. https://doi.org/10.1016/j.susmat.2020.e00169

Mikula, K., Skrzypczak, D., Izydorczyk, G., Warchoł, J., Moustakas, K., Chojnacka, K., & Witek-Krowiak, A. (2021). 3D printing filament as a second life of waste plastics—A review. *Environmental Science and Pollution Research*, *28*(10), 12321–12333. https://doi.org/10.1007/s11356-020-10657-8

Miles, M. B., & Huberman, A. M. (1994). *Qualitative Data Analysis: An Expanded Sourcebook*. California, USA: SAGE Publications Inc.

Miller, S. R., & Ross, A. D. (2003). An exploratory analysis of resource utilization across organizational units: Understanding the resource-based view. *International Journal of Operations and Production Management*, *23*(9), 1062–1083. https://doi.org/10.1108/01443570310491774

Mirata, M., & Emtairah, T. (2005). Industrial symbiosis networks and the contribution to environmental innovation: The case of the Landskrona industrial symbiosis programme. *Journal of Cleaner Production*, *13*(10), 993–1002. https://doi.org/10.1016/j.jclepro.2004.12.010

Mitchell, R. K., Agle, B. R., & Wood, D. J. (1997). Toward a Theory of Stakeholder Identification and Salience: Defining the Principle of Who and What Really Counts. *The Academy of Management Review*, *22*(4), 853–886. https://doi.org/10.2307/259247

Momo, F. da S., & Behr, A. (2021). Blockchain: Effects in Transactions Costs from Information Governance. *BAR - Brazilian Administration Review*, *18*. https://doi.org/10.1590/1807-7692bar2021200047

Monteiro, H., Carmona-Aparicio, G., Lei, I., & Despeisse, M. (2022). Energy and material efficiency strategies enabled by metal additive manufacturing – A review for the aeronautic and aerospace sectors. *Energy Reports*, *8*, 298–305. https://doi.org/10.1016/j.egyr.2022.01.035

Morkunas, V. J., Paschen, J., & Boon, E. (2019). How blockchain technologies impact your business model. *Business Horizons*, *62*(3), 295–306. https://doi.org/10.1016/j.bushor.2019.01.009

Morseletto, P. (2020). Targets for a circular economy. *Resources, Conservation and Recycling*, *153*, 104553. https://doi.org/10.1016/j.resconrec.2019.104553

Mortensen, L., & Kørnøv, L. (2019). Critical factors for industrial symbiosis emergence process. *Journal of Cleaner Production*, *212*, 56–69. https://doi.org/10.1016/j.jclepro.2018.11.222

Naghshineh, B., Ribeiro, A., Jacinto, C., & Carvalho, H. (2021). Social impacts of additive manufacturing: A stakeholder-driven framework. *Technological Forecasting and Social Change*, *164*, 120368. https://doi.org/10.1016/j.techfore.2020.120368

Nakamoto, S. (2008). Bitcoin: A Peer-to-Peer Electronic Cash System. *Decentralized Business Review*, 21260.

Nascimento, D. L. M., Alencastro, V., Quelhas, O. L. G., Caiado, R. G. G., Garza-Reyes, J. A., Rocha-Lona, L., & Tortorella, G. (2019). Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context. *Journal of Manufacturing Technology Management*. https://doi.org/10.1108/JMTM-03-2018-0071

Nava, C., & Lucanto, D. (2021). Eco-innovative scenarios for smart materials. The pvcupcycling project – circular economy and zero waste. *Smart Innovation, Systems and Technologies*, *178 SIST*, 1458–1467. https://doi.org/10.1007/978-3-030-48279-4_136

Neves, A., Godina, R., Azevedo, S. G., & Matias, J. C. O. (2020). A comprehensive review of industrial symbiosis. *Journal of Cleaner Production*, *247*, 119113. https://doi.org/10.1016/j.jclepro.2019.119113

Nikolaou, I. E., Jones, N., & Stefanakis, A. (2021). Circular Economy and Sustainability: The Past, the Present and the Future Directions. *Circular Economy and Sustainability*, *1*(1), 1–20. https://doi.org/10.1007/s43615-021-00030-3

Ning, L., & Yuan, Y. (2021). How blockchain impacts the supply chain finance platform business model reconfiguration. *International Journal of Logistics Research and Applications*, *0*(0), 1–21. https://doi.org/10.1080/13675567.2021.2017419

Niranjanamurthy, M., Nithya, B. N., & Jagannatha, S. (2019). Analysis of Blockchain technology: Pros, cons and SWOT. *Cluster Computing*, *22*(6), 14743–14757. https://doi.org/10.1007/s10586-018-2387-5

Northwood, D. O., & Faldu, N. (2020). Corrosion: The circular materials economy and design for sustainability. In *Proceedings of the Australasian Corrosion Association's Annual Conference: Corrosion and Prevention, Melbourne, Australia* (pp. 24-27)

Oettmeier, K., & Hofmann, E. (2017). Additive manufacturing technology adoption: An empirical analysis of general and supply chain-related determinants. *Journal of Business Economics*, *87*(1), 97–124. https://doi.org/10.1007/s11573-016-0806-8

Oh, J., Choi, Y., & In, J. (2022). A conceptual framework for designing blockchain technology enabled supply chains. *International Journal of Logistics Research and Applications*, *0*(0), 1–19. https://doi.org/10.1080/13675567.2022.2052824

Oliveira, M., & Gama, J. (2012). An overview of social network analysis. *WIREs Data Mining and Knowledge Discovery*, *2*(2), 99–115. https://doi.org/10.1002/widm.1048

Ordoñez, E., Neves Monteiro, S., & Colorado, H. A. (2022). Valorization of a hazardous waste with 3D-printing: Combination of kaolin clay and electric arc furnace dust from the steel making industry. *Materials & Design*, *217*, 110617. https://doi.org/10.1016/j.matdes.2022.110617

OWA. (2021). *Eco-designed 3D filaments for sustainable creativity | Responsible 3D printing | OWA*. OWA. Retrieved from: https://www.armor-owa.com/3d-printing

Pasco, J., Lei, Z., & Aranas, C. (2022). Additive Manufacturing in Off-Site Construction: Review and Future Directions. *Buildings*, *12*(1), 53. https://doi.org/10.3390/buildings12010053

Paul, T., Mondal, S., Islam, N., & Rakshit, S. (2021). The impact of blockchain technology on the tea supply chain and its sustainable performance. *Technological Forecasting and Social Change*, *173*, 121163. https://doi.org/10.1016/j.techfore.2021.121163

Paul, T., & Rakshit, S. (2022). Blockchain-Based Internet of Things: Challenges and Opportunities. Em D. De, S. Bhattacharyya, & J. J. P. C. Rodrigues (Eds.), *Blockchain based Internet of Things* (pp. 23–45). Springer. https://doi.org/10.1007/978-981-16-9260-4_2

Peck, M. (2017). Blockchain world - Do you need a blockchain? This chart will tell you if the technology can solve your problem. *IEEE Spectrum*, *54*, 38–60. https://doi.org/10.1109/MSPEC.2017.8048838

Peeters, B., Kiratli, N., & Semeijn, J. (2019). A barrier analysis for distributed recycling of 3D printing waste: Taking the maker movement perspective. *Journal of Cleaner Production*, *241*, 118313. https://doi.org/10.1016/j.jclepro.2019.118313

Piekkari, R., Welch, C., & Paavilainen, E. (2009). The Case Study as Disciplinary Convention: Evidence From International Business Journals. *Organizational Research Methods*, *12*(3), 567–589. https://doi.org/10.1177/1094428108319905

Piller, F. T., Weller, C., & Kleer, R. (2015). Business Models with Additive Manufacturing—Opportunities and Challenges from the Perspective of Economics and Management. Em C. Brecher (Ed.), *Advances in Production Technology* (pp. 39–48). Springer International Publishing.

Ponis, S., Aretoulaki, E., Maroutas, T. N., Plakas, G., & Dimogiorgi, K. (2021). A Systematic Literature Review on Additive Manufacturing in the Context of Circular Economy. *Sustainability*, *13*(11), 6007. https://doi.org/10.3390/su13116007

Ponis, S. T. (2021). Industrial Symbiosis Networks in Greece: Utilising the Power of Blockchain-based B2B Marketplaces. *The Journal of The British Blockchain Association*, *4*(1), 1–7. https://doi.org/10.31585/jbba-4-1-(4)2021

Pulidori, E., Micalizzi, S., Bramanti, E., Bernazzani, L., De Maria, C., Pelosi, C., Tinè, M. R., Vozzi, G., & Duce, C. (2022). Valorization of not soluble byproducts deriving from green keratin extraction from poultry feathers as filler for biocomposites. *Journal of Thermal Analysis and Calorimetry*, *147*(9), 5377–5390. https://doi.org/10.1007/s10973-021-11166-7

Queiroz, M. M., & Fosso Wamba, S. (2019). Blockchain adoption challenges in supply chain: An empirical investigation of the main drivers in India and the USA. *International Journal of Information Management*, *46*, 70–82. https://doi.org/10.1016/j.ijinfomgt.2018.11.021

Rabianski, J. S. (2003). Primary and secondary data: Concepts, concerns, errors, and issues. *The Appraisal Journal*, *71*(1), 43–55.

Ragin, C. C., & Becker, H. S. (1992). *What is a Case?: Exploring the Foundations of Social Inquiry*. Cambrigde, England: Cambridge University Press.

Rahito, Wahab, D. A., & Azman, A. H. (2019). Additive Manufacturing for Repair and Restoration in Remanufacturing: An Overview from Object Design and Systems Perspectives. *Processes*, *7*(11), 802. https://doi.org/10.3390/pr7110802

Rajput, S., & Singh, S. P. (2019a). Industry 4.0 − challenges to implement circular economy. *Benchmarking: An International Journal*, *28*(5), 1717–1739. https://doi.org/10.1108/BIJ-12-2018-0430

Rajput, S., & Singh, S. P. (2019b). Connecting circular economy and industry 4.0. *International Journal of Information Management*, *49*, 98–113. https://doi.org/10.1016/j.ijinfomgt.2019.03.002

Rajput, S., & Singh, S. P. (2020). Industry 4.0 Model for circular economy and cleaner production. *Journal of Cleaner Production*, *277*, 123853. https://doi.org/10.1016/j.jclepro.2020.123853

Ravindran, A., Scsavnicki, S., Nelson, W., Gorecki, P., Franz, J., Oberloier, S., Meyer, T. K., Barnard, A. R., & Pearce, J. M. (2019). Open Source Waste Plastic Granulator. *Technologies*, *7*(4), 74. https://doi.org/10.3390/technologies7040074

re:3D Inc. (2019). *[Re]Verse Pitch Competition—2019 Executive Summary*. Retrieved from: https://static1.squarespace.com/static/55b690b5e4b0491deed57b65/t/5d517acab1708d00017ffcc2/1565620941017/re3D+Executive+Summary+2019_Redacted.pdf

re:3D Inc. (2020a). *GIGABOT® – re:3D | Life-Sized Affordable 3D Printing*. Retrieved from: https://re3d.org/gigabot/

re:3D Inc. (2020b). *Trash to Treasure: From Reverse Pitch to ReStore – re:3D | Life-Sized Affordable 3D Printing*. Retrieved from: https://re3d.org/trash-to-treasure-from-reverse-pitch-to-restore/

Reed, M. S., Graves, A., Dandy, N., Posthumus, H., Hubacek, K., Morris, J., Prell, C., Quinn, C. H., & Stringer, L. C. (2009). Who's in and why? A typology of stakeholder analysis methods for natural resource management. *Journal of Environmental Management*, *90*(5), 1933–1949. https://doi.org/10.1016/j.jenvman.2009.01.001

Rehman Khan, S. A., Yu, Z., Sarwat, S., Godil, D. I., Amin, S., & Shujaat, S. (2022). The role of block chain technology in circular economy practices to improve organisational performance. *International Journal of Logistics Research and Applications*, *25*(4–5), 605–622. https://doi.org/10.1080/13675567.2021.1872512

Reich, M. J., Woern, A. L., Tanikella, N. G., & Pearce, J. M. (2019). Mechanical Properties and Applications of Recycled Polycarbonate Particle Material Extrusion-Based Additive Manufacturing. *Materials*, *12*(10), 1642. https://doi.org/10.3390/ma12101642

Reijonen, J., Jokinen, A., Puukko, P., Lagerbom, J., Lindroos, T., Haapalainen, M., & Salminen, A. (2017). Circular Economy Concept in Additive Manufacturing. *Euro PM2017 Proceedings. Euro PM2017 Congress & Exhibition. European Powder Metallurgy Association (EPMA),* Milan, Italy.

Rejeski, D., Zhao, F., & Huang, Y. (2018). Research needs and recommendations on environmental implications of additive manufacturing. *Additive Manufacturing*, *19*, 21–28. https://doi.org/10.1016/j.addma.2017.10.019

ReStore. (2021). *ReStore—Austin Habitat for Humanity*. Austin Habitat for Humanity. Retrieved from: https://austinhabitat.org/restore/

Reverse Pitch Competition. (2019). *2019 [Re]Verse Pitch*. [Re]Verse Pitch Competition. Retrieved from: https://reversepitch.org/2019-reverse-pitch

Reyna, A., Martín, C., Chen, J., Soler, E., & Díaz, M. (2018). On blockchain and its integration with IoT. Challenges and opportunities. *Future Generation Computer Systems*, *88*, 173–190. https://doi.org/10.1016/j.future.2018.05.046

Ritzén, S., & Sandström, G. Ö. (2017). Barriers to the Circular Economy – Integration of Perspectives and Domains. *Procedia CIRP*, *64*, 7–12. https://doi.org/10.1016/j.procir.2017.03.005

Rodrigues Dias, V. M., Jugend, D., de Camargo Fiorini, P., Razzino, C. do A., & Paula Pinheiro, M. A. (2022). Possibilities for applying the circular economy in the aerospace industry: Practices, opportunities and challenges. *Journal of Air Transport Management*, *102*, 102227. https://doi.org/10.1016/j.jairtraman.2022.102227

Rodriguez Delgadillo, R., Medini, K., & Wuest, T. (2022). A DMAIC Framework to Improve Quality and Sustainability in Additive Manufacturing—A Case Study. *Sustainability*, *14*(1), 581. https://doi.org/10.3390/su14010581

Ronaghi, M. H., & Mosakhani, M. (2022). The effects of blockchain technology adoption on business ethics and social sustainability: Evidence from the Middle East. *Environment, Development and Sustainability*, *24*(5), 6834–6859. https://doi.org/10.1007/s10668-021-01729-x

Rosa, P., Sassanelli, C., Urbinati, A., Chiaroni, D., & Terzi, S. (2020). Assessing relations between Circular Economy and Industry 4.0: A systematic literature review. *International Journal of Production Research*, *58*(6), 1662–1687. https://doi.org/10.1080/00207543.2019.1680896

Rosa, P., & Terzi, S. (Eds.). (2021). *New Business Models for the Reuse of Secondary Resources from WEEEs: The FENIX Project*. Springer Nature. https://doi.org/10.1007/978-3-030-74886-9

Rousseau, D. M., Manning, J., & Denyer, D. (2008). Evidence in Management and Organizational Science: Assembling the Field's Full Weight of Scientific Knowledge Through Syntheses. *The Academy of Management Annals*, *2*(1), 475–515. https://doi.org/10.1080/19416520802211651

Rowley, J. (2002). Using case studies in research. *Management Research News*, *25*(1), 16–27. https://doi.org/10.1108/01409170210782990

Rowley, T. J. (1997). Moving beyond Dyadic Ties: A Network Theory of Stakeholder Influences. *The Academy of Management Review*, *22*(4), 887–910. https://doi.org/10.2307/259248

Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2019). Blockchain technology and its relationships to sustainable supply chain management. *International Journal of Production Research*, *57*(7), 2117–2135. https://doi.org/10.1080/00207543.2018.1533261

Saboori, A., Aversa, A., Marchese, G., Biamino, S., Lombardi, M., & Fino, P. (2019). Application of Directed Energy Deposition-Based Additive Manufacturing in Repair. *Applied Sciences-Basel*, *9*(16), 3316. https://doi.org/10.3390/app9163316

Sadeghi, M., Mahmoudi, A., Deng, X., & Luo, X. (2022). Prioritizing requirements for implementing blockchain technology in construction supply chain based on circular economy: Fuzzy Ordinal Priority Approach. *International Journal of Environmental Science and Technology*. https://doi.org/10.1007/s13762-022-04298-2

Sanchez, F. A. C., Lanza, S., Boudaoud, H., Hoppe, S., & Camargo, M. (2015). *Polymer Recycling and Additive Manufacturing in an Open Source context: Optimization of processes and methods*. 1591. https://hal.univ-lorraine.fr/hal-01523136

Sanka, A. I., Irfan, M., Huang, I., & Cheung, R. C. C. (2021). A survey of breakthrough in blockchain technology: Adoptions, applications, challenges and future research. *Computer Communications*, *169*, 179–201. https://doi.org/10.1016/j.comcom.2020.12.028

Sauerwein, M., Bakker, C., & Balkenende, R. (2017). Additive manufacturing for circular product design: A literature review from a design perspective. In C. Bakker, & R. Mugge (Eds.), Plate Product Lifetimes And The Environment 2017: Conference Proceedings (pp. 358-364). (Research in Design Series; Vol. 9). IOS Press. https://doi.org/10.3233/978-1-61499-820-4-358

Sauerwein, M., Doubrovski, E., Balkenende, R., & Bakker, C. (2019). Exploring the potential of additive manufacturing for product design in a circular economy. *Journal of Cleaner Production*, *226*, 1138–1149. https://doi.org/10.1016/j.jclepro.2019.04.108

Sauerwein, M., & Doubrovski, E. L. (2018). Local and recyclable materials for additive manufacturing: 3D printing with mussel shells. *Materials Today Communications*, *15*, 214–217. https://doi.org/10.1016/j.mtcomm.2018.02.028

Schmidt, C. G., & Wagner, S. M. (2019). Blockchain and supply chain relations: A transaction cost theory perspective. *Journal of Purchasing and Supply Management*, *25*(4), 100552. https://doi.org/10.1016/j.pursup.2019.100552

Shakir, M. (2002). *The selection of case studies: Strategies and their applications to IS implementation case studies*. https://mro.massey.ac.nz/handle/10179/4373

Shanmugam, V., Das, O., Neisiany, R. E., Babu, K., Singh, S., Hedenqvist, M. S., Berto, F., & Ramakrishna, S. (2020). Polymer Recycling in Additive Manufacturing: An Opportunity for the Circular Economy. *Materials Circular Economy*, *2*(1), 11. https://doi.org/10.1007/s42824-020-00012-0

Sher, D. (2016, outubro 17). CNEA and INTI Led Project Shows that Post-Consumer Recycled Plastics Can Be Used to 3D Print Functional Devices. *3D Printing Media Network - The Pulse of the AM Industry*. https://www.3dprintingmedia.network/cnea-inti-led-project-shows-post-consumer-recycled-plastics-can-used-3d-print-functional-devices/

Shiferaw, M. Z., & Gebremedhen, H. S. (2022). Recycled Polymer for FDM 3D Printing Filament Material: Circular Economy for Sustainability of Additive Manufacturing. Em M. L. Berihun (Ed.), *Advances of Science and Technology* (pp. 243–261). Springer International Publishing. https://doi.org/10.1007/978-3-030-93712-6_17

Shojaei, A., Ketabi, R., Razkenari, M., Hakim, H., & Wang, J. (2021). Enabling a circular economy in the built environment sector through blockchain technology. *Journal of Cleaner Production*, *294*, 126352. https://doi.org/10.1016/j.jclepro.2021.126352

Silva, E. C., Candiango, J. A., Rodrigues, S. J., Sampaio, Á. M., & Pontes, A. J. (2022). Hybrid Manufacturing of Aluminium Parts Combining Additive and Conventional Technologies—Mechanical and Thermal Properties. *Journal of Manufacturing and Materials Processing*, *6*(2), 40. https://doi.org/10.3390/jmmp6020040

Singh, R., & Kumar, R. (2022). *Additive Manufacturing for Plastic Recycling: Efforts in Boosting A Circular Economy*. London, England: CRC Press, Taylor & Francis.

Singh, S., Ramakrishna, S., & Singh, R. (2017). Material issues in additive manufacturing: A review. *Journal of Manufacturing Processes*, *25*, 185–200. https://doi.org/10.1016/j.jmapro.2016.11.006

Sitadewi, D., Yudoko, G., & Okdinawati, L. (2021). Bibliographic mapping of post-consumer plastic waste based on hierarchical circular principles across the system perspective. *Heliyon*, *7*(6), e07154. https://doi.org/10.1016/j.heliyon.2021.e07154

Sivula, A., Shamsuzzoha, A. & Helo, P. (2021). Requirements for Blockchain Technology in Supply Chain Management: An Exploratory Case Study. *Operations and supply chain management: an international journal*,14(1), 39-50. http://doi.org/10.31387/oscm0440284

Spaltini, M., Poletti, A., Acerbi, F., & Taisch, M. (2021). *A quantitative framework for Industry 4.0 enabled Circular Economy*. *98*, 115–120. https://doi.org/10.1016/j.procir.2021.01.015

Stefaniak, A. B., Bowers, L. N., Cottrell, G., Erdem, E., Knepp, A. K., Martin, S. B., Pretty, J., Duling, M. G., Arnold, E. D., Wilson, Z., Krider, B., Fortner, A. R., LeBouf, R. F., Virji, M. A., & Sirinterlikci, A. (2022). Towards sustainable additive manufacturing: The need for awareness of particle and vapor releases during polymer recycling, making filament, and fused filament fabrication 3-D printing. *Resources, Conservation and Recycling*, *176*, 105911. https://doi.org/10.1016/j.resconrec.2021.105911

Stratiotou Efstratiadis, V., & Michailidis, N. (2022). Sustainable Recovery, Recycle of Critical Metals and Rare Earth Elements from Waste Electric and Electronic Equipment (Circuits, Solar, Wind) and Their Reusability in Additive Manufacturing Applications: A Review. *Metals*, *12*(5), 794. https://doi.org/10.3390/met12050794

Sundqvist, J., & Samarjy, R. S. M. (2019). High-speed imaging of droplet behaviour during the CYCLAM drop-deposition technique. *Procedia Manufacturing*, *36*, 208–215. https://doi.org/10.1016/j.promfg.2019.08.027

Sutherland, T. A. (2009). *Stakeholder value network analysis for space-based earth observations* (Master Thesis, Massachusetts Institute of Technology). Retrieved from: https://dspace.mit.edu/handle/1721.1/63181

Szabo, N. (1997). Formalizing and Securing Relationships on Public Networks. *First Monday*, *2*(9). https://doi.org/10.5210/fm.v2i9.548

Tan, L. J., Zhu, W., & Zhou, K. (2020). Recent Progress on Polymer Materials for Additive Manufacturing. *Advanced Functional Materials*, *30*(43), 2003062. https://doi.org/10.1002/adfm.202003062

Tavares, T. M., Filho, M. G., Ganga, G. M. D., & Callefi, M. H. B. M. (2020). The relationship between additive manufacturing and circular economy: A sistematic review. *Independent Journal of Management & Production*, *11*(5), 1648–1666. https://doi.org/10.14807/ijmp.v11i5.1290

Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. *British Journal of Management*, *14*(3), 207–222. https://doi.org/10.1111/1467-8551.00375

Treiblmaier, H. (2018). The impact of the blockchain on the supply chain: A theory-based research framework and a call for action. *Supply Chain Management: An International Journal*, *23*(6), 545–559. https://doi.org/10.1108/SCM-01-2018-0029

Tseng, M.-L., Tan, R. R., Chiu, A. S. F., Chien, C.-F., & Kuo, T. C. (2018). Circular economy meets industry 4.0: Can big data drive industrial symbiosis? *Resources, Conservation and Recycling*, *131*, 146–147. https://doi.org/10.1016/j.resconrec.2017.12.028

Turner, C., Moreno, M., Mondini, L., Salonitis, K., Charnley, F., Tiwari, A., & Hutabarat, W. (2019). Sustainable Production in a Circular Economy: A Business Model for Re-Distributed Manufacturing. *Sustainability*, *11*(16), 4291. https://doi.org/10.3390/su11164291

Unruh, G. (2018). Circular Economy, 3D Printing, and the Biosphere Rules. *California Management Review*, *60*(3), 95–111. https://doi.org/10.1177/0008125618759684

Upadhyay, N. (2020). Demystifying blockchain: A critical analysis of challenges, applications and opportunities. *International Journal of Information Management*, *54*, 102120. https://doi.org/10.1016/j.ijinfomgt.2020.102120

Vaidya, S., Ambad, P., & Bhosle, S. (2018). Industry 4.0 – A Glimpse. *Procedia Manufacturing*, *20*, 233–238. https://doi.org/10.1016/j.promfg.2018.02.034

Vayre, B., Vignat, F., & Villeneuve, F. (2012). Metallic additive manufacturing: State-of-the-art review and prospects. *Mechanics & Industry*, *13*(2), 89–96. https://doi.org/10.1051/meca/2012003

Vidakis, N., Petousis, M., Maniadi, A., Koudoumas, E., Vairis, A., & Kechagias, J. (2020). Sustainable Additive Manufacturing: Mechanical Response of Acrylonitrile-Butadiene-Styrene over Multiple Recycling Processes. *Sustainability*, *12*(9), 3568. https://doi.org/10.3390/su12093568

Voet, V. S. D., Strating, T., Schnelting, G. H. M., Dijkstra, P., Tietema, M., Xu, J., Woortman, A. J. J., Loos, K., Jager, J., & Folkersma, R. (2018). Biobased Acrylate Photocurable Resin Formulation for Stereolithography 3D Printing. *ACS Omega*, *3*(2), 1403–1408. https://doi.org/10.1021/acsomega.7b01648

Výtisk, J., Honus, S., Kočí, V., Pagáč, M., Hajnyš, J., Vujanovic, M., & Vrtek, M. (2022). Comparative study by life cycle assessment of an air ejector and orifice plate for experimental measuring stand manufactured by conventional manufacturing and additive manufacturing. *Sustainable Materials and Technologies*, *32*, e00431. https://doi.org/10.1016/j.susmat.2022.e00431

Wang, Y., Chen, C. H., & Zghari-Sales, A. (2021). Designing a blockchain enabled supply chain. *International Journal of Production Research*, *59*(5), 1450–1475. https://doi.org/10.1080/00207543.2020.1824086

Weaver, E., O'Hagan, C., & Lamprou, D. A. (2022). The sustainability of emerging technologies for use in pharmaceutical manufacturing. *Expert Opinion on Drug Delivery*, *19*(7), 861–872. https://doi.org/10.1080/17425247.2022.2093857

Welch, C., & Piekkari, R. (2017). How should we (not) judge the 'quality' of qualitative research? A re-assessment of current evaluative criteria in International Business. *Journal of World Business*, *52*. https://doi.org/10.1016/j.jwb.2017.05.007

Welch, C., Piekkari, R., Plakoyiannaki, E., & Paavilainen-Mäntymäki, E. (2011). Theorising from case studies: Towards a pluralist future for international business research. *Journal of International Business Studies*, *42*(5), 740–762. https://doi.org/10.1057/jibs.2010.55

Wilts, E. M., & Long, T. E. (2021). Sustainable additive manufacturing: Predicting binder jettability of water-soluble, biodegradable and recyclable polymers. *Polymer International*, *70*(7), 958–963. https://doi.org/10.1002/pi.6108

Woern, A. L., Byard, D. J., Oakley, R. B., Fiedler, M. J., Snabes, S. L., & Pearce, J. M. (2018). Fused Particle Fabrication 3-D Printing: Recycled Materials' Optimization and Mechanical Properties. *Materials*, *11*(8). https://doi.org/10.3390/ma11081413

Woern, A. L., McCaslin, J. R., Pringle, A. M., & Pearce, J. M. (2018). RepRapable Recyclebot: Open source 3-D printable extruder for converting plastic to 3-D printing filament. *HardwareX*, *4*, e00026. https://doi.org/10.1016/j.ohx.2018.e00026

Woern, A. L., & Pearce, J. M. (2018). 3-D Printable Polymer Pelletizer Chopper for Fused Granular Fabrication-Based Additive Manufacturing. *Inventions*, *3*(4), 78. https://doi.org/10.3390/inventions3040078

Woiceshyn, J., & Daellenbach, U. (2018). Evaluating inductive vs deductive research in management studies: Implications for authors, editors, and reviewers. *Qualitative Research in Organizations and Management: An International Journal*, *13*(2), 183–195. https://doi.org/10.1108/QROM-06-2017-1538

Wu, H., Mehrabi, H., Karagiannidis, P., & Naveed, N. (2022). Additive manufacturing of recycled plastics: Strategies towards a more sustainable future. *Journal of Cleaner Production*, *335*, 130236. https://doi.org/10.1016/j.jclepro.2021.130236

Wüst, K., & Gervais, A. (2018). Do you Need a Blockchain? *2018 Crypto Valley Conference on Blockchain Technology (CVCBT)*, 45–54. https://doi.org/10.1109/CVCBT.2018.00011

Xiang, P., & Yuan, T. (2019). A collaboration-driven mode for improving sustainable cooperation in smart industrial parks. *Resources, Conservation and Recycling*, *141*, 273–283. https://doi.org/10.1016/j.resconrec.2018.10.037

Xu, L. D., & Viriyasitavat, W. (2019). Application of Blockchain in Collaborative Internet-of-Things Services. *IEEE Transactions on Computational Social Systems*, *6*(6), 1295–1305. https://doi.org/10.1109/TCSS.2019.2913165

Xue, X., Dou, J., & Shang, Y. (2020). Blockchain-driven supply chain decentralized operations – information sharing perspective. *Business Process Management Journal*, *27*(1), 184–203. https://doi.org/10.1108/BPMJ-12-2019-0518

Yaga, D., Mell, P., Roby, N., & Scarfone, K. (2018). Blockchain Technology Overview. *arXiv:1906.11078 [cs]*, NIST IR 8202. https://doi.org/10.6028/NIST.IR.8202

Yeo, Z., Masi, D., Low, J. S. C., Ng, Y. T., Tan, P. S., & Barnes, S. (2019). Tools for promoting industrial symbiosis: A systematic review. *Journal of Industrial Ecology*, *23*(5), 1087–1108. https://doi.org/10.1111/jiec.12846

Yin, R. K. (1994). *Case study research: Design and methods* (Third Ed, Vol. 5). Sage Publications, Inc.

Yin, R. K. (2009). *Case Study Research: Design and Methods* (Fourth Ed). Sage Publications, Inc.

Yuen, T. H. (2020). PAChain: Private, authenticated & auditable consortium blockchain and its implementation. *Future Generation Computer Systems*, *112*, 913–929. https://doi.org/10.1016/j.future.2020.05.011

Yusoh, S. S. M., Wahab, D. A., Habeeb, H. A., & Azman, A. H. (2021). Intelligent systems for additive manufacturing-based repair in remanufacturing: A systematic review of its potential. *PeerJ Computer Science*, *7*, e808. https://doi.org/10.7717/peerj-cs.808

Zander, N. E. (2019). Recycled Polymer Feedstocks for Material Extrusion Additive Manufacturing. In *Polymer-Based Additive Manufacturing: Recent Developments*. American Chemical Society (Vol. 1315, pp. 37–51). https://doi.org/10.1021/bk-2019-1315.ch003

Zhu, Q., Geng, Y., & Lai, K. (2010). Circular economy practices among Chinese manufacturers varying in environmental-oriented supply chain cooperation and the performance implications. *Journal of Environmental Management*, *91*(6), 1324–1331. https://doi.org/10.1016/j.jenvman.2010.02.013

APPENDIX A

Table A-1 contains the detailed analysis that was performed for the sample of 83 documents, found in the databases "Web of Science" and "Scopus", from 2014 until 2022. The analysis was performed according to the defined categories in Table 2-4 in sub-chapter 2.1.3.

Table A-1 Characteristics of the selected papers in the sample.

Authors, years	Pub. Type	Journal/ Conference	Domain	Research methods	4R's principle	Potential IS characteristics		Technology	Materials used
						Exchange of resources	Type of resources		
(Pasco et al., 2022)	Int. Journal	Buildings	Construction & Building Technology; Engineering	A	Reduce	No	N/A	Fused deposition modeling, binder jetting, powder bed fusion, directed-energy deposition	N/A
(Almonti et al., 2022)	Int. Journal	Int. J. of Advanced Manufacturing Technology	Automation & Control Systems; Engineering	E	Recycle	Yes	Waste	Electron beam melting and selective laser melting	Biological waste
(Monteiro et al., 2022)	Conf.	8th Int. Conf. on Energy and Environment Research (ICEER) - Developing the World in 2021 with Clean and Safe Energy	Energy & Fuels	E	Reduce	No	N/A	Metal additive manufacturing	N/A
(de Rubeis, 2022)	Int. Journal	Sustainability	Science & Technology - Other Topics: Environmental Sciences & Ecology	E	Reuse, Recycle	Yes	Waste	Fused deposition modeling, fused filament fabrication, stereolithography, selective laser sintering	Polystyrene and wool
(Fico et al., 2022)	Int. Journal	J. of Building Engineering	Construction & Building Technology; Engineering	E	Recycle	Yes	Materials and waste	Fused filament fabrication	Polylactic acid and olive wood scraps

Table A-1 Characteristics of the selected papers in the sample. (cont.)

Authors, years	Pub. Type	Journal/ Conference	Domain	Research methods	4R's principle	Potential IS characteristics		Technology	Materials used
						Exchange of resources	Type of resources		
(Gouveia et al., 2022)	Int. Journal	Sustainability	Science & Technology - Other Topics; Environmental Sciences & Ecology	E	Reuse	No	N/A	Direct energy deposition	Steel powder
(Silva et al., 2022)	Int. Journal	J. of Manufacturing and Materials Processing	Engineering; Materials Science	E	Reuse	No	N/A	Powder bed fusion	Aluminum powder and alloys
(Ertz et al., 2022)	Int. Journal	Industrial Marketing Management	Business & Economics	E	Reduce	No	N/A	N/A	N/A
(He et al., 2022)	Int. Journal	J. of Industrial Ecology	Science & Technology - Other Topics; Engineering; Environmental Sciences & Ecology	E	Recycle	Yes	Waste	Selective laser sintering	Waste polymer powders
(Stratiotou Efstratiadis & Michailidis, 2022)	Int. Journal	Metals	Materials Science; Metallurgy & Metallurgical Engineering	E	Recycle	Yes	Waste	Fused deposition modeling	Waste electric and electronic equipment
(Rodrigues Dias et al., 2022)	Int. Journal	J. of Air Transport and Management	Transportation	E	Reuse, Recycle	No	N/A	N/A	N/A
(Hennemann Hilario da Silva & Sehnem, 2022)	Int. Journal	Rege - Revista de Gestão	Business & Economics	A	Reuse, Recycle	No	N/A	N/A	N/A

Table A-1 Characteristics of the selected papers in the sample. (cont.)

Authors, years	Pub. Type	Journal/ Conference	Domain	Research methods	4R's principle	Potential IS characteristics		Technology	Materials used
						Exchange of resources	Type of resources		
(Devarajan et al., 2022)	Int. Journal	J. of Nanomaterials	Science & Technology - Other Topics; Materials Science	E	Recycle	Yes	Waste	Direct writing forming	Nonsegregated waste material (food, plastics, e-waste)
(Ordoñez et al., 2022)	Int. Journal	Materials & Design	Materials Science	E	Recycle	Yes	Waste	Direct ink writing	Electric arc furnace steel dust waste
(Bitting et al., 2022)	Int. Journal	Biomimetics	Engineering; Materials Science	A	Recycle	Yes	Waste	Direct ink writing, fused deposition modeling and bio-ink	Mycelium-based materials
(Stefaniak et al., 2022)	Int. Journal	Resource, Conservation and Recycling	Engineering; Environmental Sciences & Ecology	E	Reuse, recycle	Yes	Waste	Fused filament fabrication	Acrylonitrile butadiene styrene and polylactic plastic waste and polypropylene pellets
(de León et al., 2022)	Int. Journal	ACS Applied Polymer Materials	Materials Science; Polymer Science	E	Recycle	Yes	Waste	Fused deposition modeling	Cork powder
(Výtisk et al., 2022)	Int. Journal	Sustainable Materials and Technologies	Science & Technology - Other Topics; Energy & Fuels; Materials Science	E	Recycle	No	N/A	Selective laser melting	Metallic powder (steel)
(Chalissery et al., 2022)	Int. Journal	Macromolecular Materials and Engineering	Materials Science; Polymer Science	E	Reuse	No	N/A	Fused filament fabrication	Polyether urethane

Table A-1 Characteristics of the selected papers in the sample. (cont.)

Authors, years	Pub. Type	Journal/ Conference	Domain	Research methods	4R's principle	Potential IS characteristics		Technology	Materials used
						Exchange of resources	Type of resources		
(Pulidori et al., 2022)	Int. Journal	J. of Thermal Analysis and Calorimetry	Thermodynamics; Chemistry	E	Recycle	Yes	Waste and materials	Fused deposition modeling	Poultry feathers wastes and polylactic acid
(Barkane et al., 2022)	Int. Journal	3D Printing and Additive Manufacturing	Engineering; Materials Science	E	Recycle	Yes	Waste	Stereolithography	Biobased polymer resins (from vegetable oils)
(Andrew & Dhakal, 2022)	Int. Journal	Composites	Materials Science	A	Reuse	No	N/A	Fused filament fabrication	Biocomposites
(Kromoser et al., 2022)	Int. Journal	Construction and Building Materials	Engineering; Materials Science	E	Recycle	Yes	Waste	Fused deposition modeling, fused filament fabrication	Wood
(Weaver et al., 2022)	Int. Journal	Expert Opinion on Drug Delivery	Pharmacology, Toxicology and Pharmaceutics	E	Reuse, Recycle	No	N/A	Powder-bed technologies	Microfluids
(de Mattos Nascimento et al., 2022)	Int. Journal	J. of Manufacturing Technology Management	Engineering; Business & Economics	A	Recycle	Yes	Waste	N/A	Metal scraps
(Elsacker et al., 2022)	Int. Journal	Sustainable Futures	Business, Management and Accounting; Decision Sciences; Social Sciences	E	Recycle	No	N/A	Extrusion-based technique	Mycelium materials
(Shiferaw & Gebremedhen, 2022)	Conf.	9th EAI Int. Conf. on Advancement of Science and Technology, ICAST 2021	Computer Science	E	Recycle	Yes	Waste	Fused deposition modeling	Post-consumer plastic waste

Table A-1 Characteristics of the selected papers in the sample. (cont.)

Authors, years	Pub. Type	Journal/ Conference	Domain	Research methods	4R's principle	Potential IS characteristics		Technology	Materials used
						Exchange of resources	Type of resources		
(Burmaoglu et al., 2022)	Int. Journal	Int. J. of Productivity and Performance Management	Business & Economics	E	Recycle	No	N/A	N/A	N/A
(Laskurain-Iturbe et al., 2021)	Int. Journal	J. of Cleaner Production	Science & Technology - Other Topics; Engineering Environmental Sciences & Ecology	E	Reduce, Reuse, Recycle, Recover	No	N/A	N/A	N/A
(Aziz et al., 2021)	Int. Journal	J. of Cleaner Production	Science & Technology - Other Topics; Engineering Environmental Sciences & Ecology	A	Reuse, Recycle	No	N/A	Powder bed fusion and Directed Energy deposition	N/A
(Ponis et al., 2021)	Int. Journal	Sustainability	Science & Technology - Other Topics; Environmental Sciences & Ecology	E	Reuse, Recycle	No	N/A	N/A	Plastic, metal, e-waste, magnets, glass, sand, concrete and rubber tires
(Ferreira et al., 2021)	Int. Journal	Sustainability	Science & Technology - Other Topics; Environmental Sciences & Ecology	E	Recycle	Yes	Waste	Fused particle fabrication, fused granular fabrication, selective laser melting	Acrylonitrile butadiene styrene, polypropylene, mussel shell, polycarbonate, polylactic acid, metallic scrap

Table A-1 Characteristics of the selected papers in the sample. (cont.)

Authors, years	Pub. Type	Journal/ Conference	Domain	Research methods	4R's principle	Potential IS characteristics		Technology	Materials used
						Exchange of resources	Type of resources		
(Priarone et al., 2021)	Int. Journal	CIRP Journal of Manufacturing Science and Technology	Engineering	E	Reuse	No	N/A	Wire and Arc Additive Manufacturing	H13 steel
(Yusoh et al., 2021)	Int. Journal	Peer J Computer Science	Computer Science	E	Reuse	No	N/A	Direct energy deposition	N/A
(Laoutid et al., 2021)	Int. Journal	Materials	Chemistry; Materials Science; Metallurgy & Metallurgical Engineering; Physics	E	Recycle	Yes	Waste	Fused deposition modeling	Acrylonitrile butadiene styrene recycled rubber tires
(Cress et al., 2021)	Int. Journal	J. of Cleaner Production	Science & Technology - Other Topics; Engineering; Environmental Sciences & Ecology	E	Recycle	No	N/A	Fused deposition modeling	Virgen and recycled acrylonitrile butadiene styrene
(Adaloudis & Bonnin Roca, 2021)	Int. Journal	J. of Cleaner Production	Science & Technology - Other Topics; Engineering; Environmental Sciences & Ecology	E	Reduce	No	N/A	Concrete 3D printing	Concrete
(Escursell et al., 2021)	Int. Journal	J. of Cleaner Production	Science & Technology - Other Topics; Engineering; Environmental Sciences & Ecology	A	Recycle	No	N/A	N/A	Polymers

Table A-1 Characteristics of the selected papers in the sample. (cont.)

Authors, years	Pub. Type	Journal/ Conference	Domain	Research methods	4R's principle	Potential IS characteristics		Technology	Materials used
						Exchange of resources	Type of resources		
(Sitadewi et al., 2021)	Int. Journal	Heliyon	Science & Technology - Other Topics	E	Reduce, reuse, recycle, recover	No	N/A	N/A	N/A
(Häußler et al., 2021)	Int. Journal	Nature	Science & Technology - Other Topics	E	Recycle	Yes	Waste	Fused filament fabrication	Polyethylene
(Maldonado-García et al., 2021)	Int. Journal	Composites	Materials Science	E	Recycle	Yes	N/A	Fused filament fabrication	Ocean plastics waste with agro-industrial pyrolyzed biomass waste
(Bergonzi & Vettori, 2021)	Int. Journal	Material Design and Processing Communications	Engineering	E	Recycle	Yes	Waste	Fused deposition modeling	Polyethylene terephthalate glycol
(Wilts & Long, 2021)	Int. Journal	Polymer International	Chemistry; Materials Science	A	Reuse, Recycle	No	N/A	Binder jetting	Polymers
(Grasso et al., 2021)	Int. Journal	Procedia Environmental Science, Engineering and Management	Environmental Science	E	Recycle	No	N/A	Fused deposition modeling	Thermoplastic materials
(Fanta et al., 2021)	Conf.	30th Int. Conf. of the International Association for Management of Technology: MOT for the World of the Future, IAMOT 2021	Business, Management and Accounting	A	Reuse, Recycle	No	N/A	N/A	N/A

Table A-1 Characteristics of the selected papers in the sample. (cont.)

Authors, years	Pub. Type	Journal/ Conference	Domain	Research methods	4R's principle	Potential IS characteristics		Technology	Materials used
						Exchange of resources	Type of resources		
(Ganter, Ehlers, et al., 2021)	Conf.	23rd Int. Conf. on Engineering Design, ICED 2021	Computer Science; Mathematics	E	Reuse	No	N/A	Laser powder bed fusion	Wheel carrier
(Ganter, Bode, et al., 2021)	Conf.	3rd Int. Conf. on Engineering Design, ICED 2021	Computer Science; Mathematics	E	Reuse	No	N/A	Laser powder bed fusion	Piston of an internal combustion engine
(Spaltini et al., 2021)	Conf.	28th CIRP Conf. on Life Cycle Engineering, LCE 2021	Engineering	A	Reduce, Reuse, Recycle, Recover	No	N/A	N/A	N/A
(Nava & Lucanto, 2021)	Conf.	4th Int. Symposium on New Metropolitan Perspectives, NMP 2020	Engineering; Economics	E	Recycle	No	N/A	N/A	PVC from eletric cables
(Meyer et al., 2020)	Int. Journal	Sustainable Materials and Technologies	Materials Science; Engineering	E	Recycle	No	N/A	N/A	Stam sand and acrylonitrile styrene acrylate
(Northwood & Faldu, 2020)	Conf.	Australasian Corrosion Association's Annual Conf.	Materials Science; Physics	E	Reuse, Recycle	No	N/A	N/A	N/A

Table A-1 Characteristics of the selected papers in the sample. (cont.)

Authors, years	Pub. Type	Journal/ Conference	Domain	Research methods	4R's principle	Potential IS characteristics		Technology	Materials used
						Exchange of resources	Type of resources		
(DePalma et al., 2020)	Int. Journal	J. Cleaner Production	Science & Technology - Environmental Sciences & Ecology	A	Recycle	No	N/A	Selective laser sintering, fused deposition modelling	Acrylonitrile butadiene styrene and Polyamide 12
(Cruz Sanchez et al., 2020)	Int. Journal	J. Cleaner Production	Science & Technology Engineering; Environmental Sciences & Ecology	E	Recycle	No	N/A	N/A	N/A
(Dertinger et al., 2020)	Int. Journal	Resources, Conservation & Recycling	Engineering; Environmental Sciences & Ecology	E	Recycle	No	N/A	Fused Filament fabrication, fused particle fabrication	Windshield wiper blade
(Arrizubieta et al., 2020)	Int. Journal	Metals	Materials Science; Metallurgy & Metallurgical; Engineering	E	Reuse, Recycle	No	N/A	N/A	Metal Powders
(Dev et al., 2020)	Int. Journal	Resources, Conservation & Recycling	Engineering; Environmental Sciences & Ecology	E	Recycle	No	N/A	N/A	N/A
(Handawi et al., 2020)	Int. Journal	J. of Mechanical Design	Engineering	E	Recycle	No	N/A	Direct energy deposition	Structural aeroengine component

Table A-1 Characteristics of the selected papers in the sample. (cont.)

Authors, years	Pub. Type	Journal/ Conference	Domain	Research methods	4R's principle	Potential IS characteristics		Technology	Materials used
						Exchange of resources	Type of resources		
(Dal Fabbro et al., 2020)	Int. Journal	Rapid Prototyping Journal	Engineering	E	Reuse	No	N/A	Fused filament fabrication, fused deposition modeling	Acrylonitrile butadiene styrene
(Sundqvist & Samarjy, 2019)	Conf.	Procedia Manufacturing	Engineering	A	Recycle	No	N/A	Laser cutting	Metal Waste
(Kuzman et al., 2019)	Conf.	WoodEMA Annual International Scientific Conf.	Sciences & Technology; Mechanics & Technology; Engineering	E	Recycle	No	N/A	Fused deposition modeling	Polylactic acid and commercial wood
(Ravindran et al., 2019)	Int. Journal	Technologies	Engineering	E	Recycle	No	N/A	Fused particle fabrication, fused granular fabrication	Post-consumer waste, 3D printed products and 3D printer wastes
(Rahito et al., 2019)	Int. Journal	Processes	Engineering	E	Reuse, Recycle	No	N/A	Direct energy deposition, powder bed fusion, cold spray technology	N/A
(Turner et al., 2019)	Int. Journal	Sustainability	Science & Technology; Environmental Sciences & Ecology	E	Reduce, Reuse	No	N/A	Selective laser sintering	N/A

Table A-1 Characteristics of the selected papers in the sample. (cont.)

Authors, years	Pub. Type	Journal/ Conference	Domain	Research methods	4R's principle	Potential IS characteristics		Technology	Materials used
						Exchange of resources	Type of resources		
(Saboori et al., 2019)	Int. Journal	Applied Sciences - Basel	Chemistry; Engineering; Materials Science; Physics	E	Reuse	No	N/A	Directed energy deposition	N/A
(Sauerwein et al., 2019)	Int. Journal	J. Cleaner Production	Science & Technology; Engineering; Environmental Sciences & Ecology	E	Reduce	No	N/A	N/A	N/A
(Reich et al., 2019)	Int. Journal	Materials	Materials Science	E	Recycle	Yes	Waste	Fused particle fabrication, fused granular fabrication	Polycarbonate
(Byard et al., 2019)	Int. Journal	Additive Manufacturing	Engineering; Materials Science	E	Recycle	Yes	Waste	Fused particle fabrication, fused granular fabrication	Acrylonitrile butadiene styrene and polypropylene
(Nascimento et al., 2019)	Int. Journal	J. Manufacturing Technology Management	Business & Economics; Engineering	E	Reuse, Recycle	No	N/A	Selective laser sintering	N/A
(Woern & Pearce, 2018)	Int. Journal	Inventions	Materials Science; Engineering	E	Recycle	No	N/A	Fused particle fabrication, fused granular fabrication	Polylactic acid and acrylonitrile butadiene styrene

Table A-1 Characteristics of the selected papers in the sample. (cont.)

Authors, years	Pub. Type	Journal/ Conference	Domain	Research methods	4R's principle	Potential IS characteristics		Technology	Materials used
						Exchange of resources	Type of resources		
(Woern, Byard, et al., 2018)	Int. Journal	Materials	Materials Science	E	Recycle	Yes	Waste	Fused particle fabrication, fused granular fabrication	Polylactic acid, Acrylonitrile butadiene styrene, Polyethylene terephthalate and Polypropylene
(Sauerwein & Doubrovski, 2018)	Int. Journal	Materials Today Communications	Materials Science	E	Reuse	Yes	Materials and waste	Binder jetting	Mussel shells waste
(Unruh, 2018)	Int. Journal	California Management Review	Business & Economics	O	Reduce, Reuse, Recycle, Recover	No	N/A	N/A	N/A
(Voet et al., 2018)	Int. Journal	ACS Omega	Chemistry	E	Reduce	No	N/A	Stereolithography	Biobased acrylate resins
(Clemon & Zohdi, 2018)	Int. Journal	Construction and Building Materials	Construction & Building Technology; Engineering; Materials Science	O	Recycle	No	N/A	N/A	N/A
(Lahrour & Brissaud, 2018)	Conf.	CIRP Life Cycle Engineering Conf.	Science & Tecnology;	O	Recycle	No	N/A	N/A	N/A
(Reijonen et al., 2017)	Conf.	Int. Powder Metallurgy Congress and Exhibition	Engineering	E	Recycle	Yes	Waste	Selective laser melting	Scrap feedstock

Table A-1 Characteristics of the selected papers in the sample. (cont.)

Authors, years	Pub. Type	Journal/ Conference	Domain	Research methods	4R's principle	Potential IS characteristics		Technology	Materials used
						Exchange of resources	Type of resources		
(Angioletti et al., 2017)	Conf.	IFIP Advances in Information and Communication Technology	Decision Sciences	A	Reduce, Reuse, Recycle	No	N/A	N/A	N/A
(Despeisse et al., 2017)	Int. Journal	Technological Forecasting and Social Change	Business & Economics, Public Administration	O	Reduce, Reuse, Recycle, Recover	No	N/A	N/A	N/A
Alghamdi et al. (2017)	Conf.	Sustainable Design and Manufacturing	Engineering	O	Recycle	No	N/A	Direct energy deposition, powder bed fusion	N/A
(Sauerwein et al., 2017)	Conf.	Product Lifetimes and The Environment (Plate)	Business & Economics; Science & Technology	E	Reduce, Reuse, Recycle	No	N/A	N/A	N/A
(Angioletti et al., 2016)	Conf.	Smart Innovation, Systems and Technologies	Decision Sciences	E	Reuse, Recycle	No	N/A	N/A	N/A
(Leino et al., 2016)	Int. Journal	Laser Assisted Net Shape Engineering 9 Int. Conf.	Engineering; Optics; Physics	E	Reduce, Reuse, Recycle	No	N/A	Direct energy deposition, powder bed fusion	N/A
(Giurco et al., 2014)	Int. Journal	Resources	Environmental Science	A	Reuse	No	N/A	N/A	N/A

APPENDIX B

Questionnaire B.1

Industrial symbiosis networks within the additive manufacturing industry

This questionnaire intends to explore the process of developing an industrial symbiosis network in the additive manufacturing context.

Industrial symbiosis is a cooperative model that aims to improve resources to gain more significant mutual benefits than the benefits obtained individually. Different entities interact with each other through exchanging resources in a value network – the industrial symbiosis network. However, the concept of industrial symbiosis is marginally exploited in the context of additive manufacturing; this emerging technology has disruptive potential regarding using different materials as secondary raw materials.

Your contribution is extremely important for the development of this study. Please accept to collaborate with this investigation through the filling of this questionnaire.

Please answer the following questions:

1 –WASTE'S IDENTIFICATION AND CHARACTERISTICS

1.1 Waste's identification (name) and its main characteristics (shape, dimensions, composition/materials):

1.2 Waste's origin (where it came from or in what process(es) are produced the by-product):

1.3 Identification of the final product that will be produced incorporating the waste:

1.4 Identification of the process(es) needed for waste recycling (for example: sorting, cleaning, melting, extrusion, among others.):

1.5 Who or which entity is responsible for the recycling process (including all the necessary waste treatment):

2 – STAKEHOLDERS' AND FLOWS' IDENTIFICATION

*By stakeholder, we consider the group of actors who participate, influence or have an interest in the symbiosis relationship

2.1 Identification of the stakeholders involved in the process (examples are companies, universities, labs, non-governmental organizations, etc.):

2.2 Identification of the exchanges that occur between the stakeholders (exchanges include: information, material, infrastructures, etc.):

2.3 Identification of to whom is sell the final product (produced using the waste):

2.4 Identification of any needs for waste transportation (please specify: What are the material needs transportation, whose responsibility it is, and how are the materials transported):

3 - COMPANY'S PROFILE

3.1 Company/organization name (optional):

3.2 Business volume in 2019 (if applicable):

3.3 Number of employees (please choose the option that suits the best):

<10	10-49	50-250	>250

3.4 Company's age (please choose the option that suits the best):

<2 years	2-5 years	5-10 years	>10 years

3.5 Identification of the type of 3D printing equipment that the company has:

3.6 Year when the additive technology was introduced in the company (if applicable):

3.7 Identification of the company's main products:

3.8 Identification of the main sector of economic activity of the company's clients:

4 - RESPONDENT'S PROFILE

4.1 Function/job:

4.2 Professional experience (years):

THE END.

THANKS FOR YOUR COLLABORATION.

Questionnaire B.2

Industrial symbiosis networks within additive manufacturing industry (re:3D and Austin ReStore)

This questionnaire intends to explore the process of developing an industrial symbiosis network in the additive manufacturing context. Your contribution is extremely important for the development of this study. Please accept to collaborate with this investigation through the filling of this questionnaire.

I - Identification of the value flows exchanged within the network

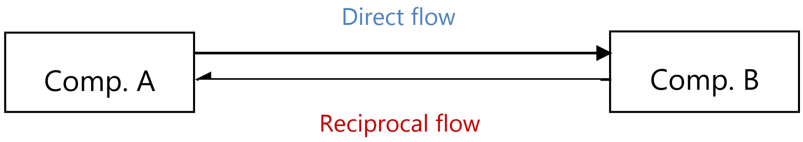
At this stage of the research, there is a need to quantify the value flows that are exchanged within the symbiotic network, and in order to do it, there are some elements that need to be considered (table 1), namely:

Table 1 - Description of the main elements to be considered

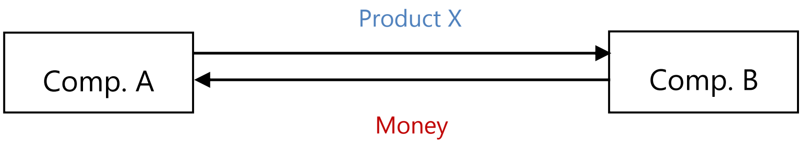
Value	A beneficial action for the participant who practises it. Stakeholders can exchange value directly or indirectly, through resource sharing or exchanges of information and knowledge.
Resource	Essentially everything that a participant in the value network considers as valuable.
Value Flow	It represents a value delivery between two stakeholders, for example, a normal transaction of buying a product has two value flows that can define it: one for the product and other for the money.

There are two types of flows:

- Direct – flow exchange from company A to company B and
- Reciprocal flow – from company B to company A.



For example, if company A produces a product that sells to company B, in exchange for money, there is a direct value flow from company A to company B that corresponds to the product that is sold. The reciprocal flow corresponds to the money that company B gives to company A in exchange for the product.



For this specific case study, and after the first questionnaire, the researchers mapped the network with the flows exchanged (fig.1) between the stakeholders and for each value flow, the direct and reciprocal flows were identified as follows (table 2). **Please validate the information below and mark your changes in case of change.**

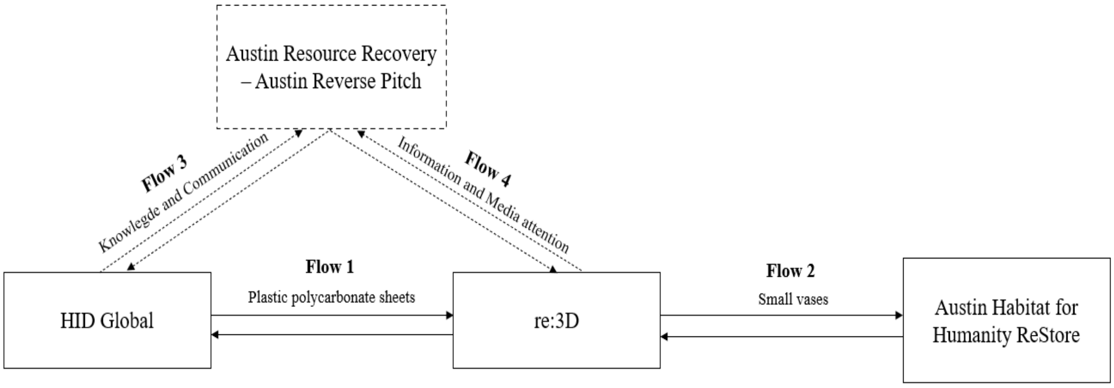


Figure 1 – Industrial Symbiosis Network inherent to the project "*Trash to Treasure*"

Table 2 – Direct and reciprocal flows of the ISN from the "Trash To Treasure" project

Flow nr.	Direct flow	Reciprocal flow
1	Plastic polycarbonate sheets	Information and Knowledge
2	Home goods and art pieces	Infrastructures and Monetary
3	Knowledge and communication	Network connections and media attention
4	Information and Media Attention	Information, Network connections and Funding

II – Quantifying the value flows

After identifying the value flows, there is a need to quantify them. Therefore, the researchers consider the attributes "urgency" and "dependence" to identify the relative importance of value flows in the symbiosis network, namely:

- **Urgency attribute** - defined by the urgency for the receiving stakeholder to get a certain resource (scores given in table 1).

Table 1 – Urgency score and levels according to Feng et al. (2013, p.160).

Urgency score	Urgency levels
0.11	It can be fulfilled after four years from now
0.22	It should be fulfilled between the third and fourth year from now
0.33	It should be fulfilled between the second and third year from now
0.66	It must be fulfilled next year
0.98	It must be fulfilled this year

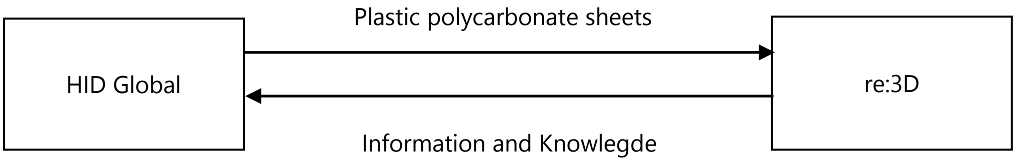
- **Dependence attribute** - this score aims to measure the dependence of a specific stakeholder to supply a particular resource. This score reveals the number of alternatives of variety in providing a resource. The higher the reliance on a stakeholders' provisions of a resource (e.g., if there are just one source and no available alternatives for a specific resource), a higher score of dependence is awarded (Ferreira et al., 2019).

Table 2 – Dependency score and levels according to Feng et al. (2013, p. 161).

Dependence score	Dependence levels
0.11	Not important – I do not need this source to fulfil this need
0.33	Somewhat important – It is acceptable that this source fulfils this need
0.55	Important – It is preferable that this source fulfils this need
0.78	Very important – It is strongly desirable that this source fulfils this need
0.98	Extremely important – It is indispensable that this source fulfils this need

For each value flow where re:3D and Restore participate in (namely, flows 1, 2 and 4) please choose the suitable punctuation for each criteria.

Flow 1:



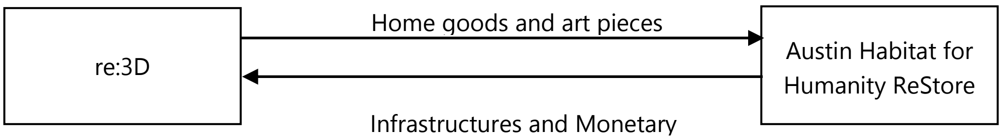
Direct: Plastic polycarbonate sheets

Urgency score	Dependence score

Reciprocal: Information and Knowledge

Urgency score	Dependence score

Flow 2:



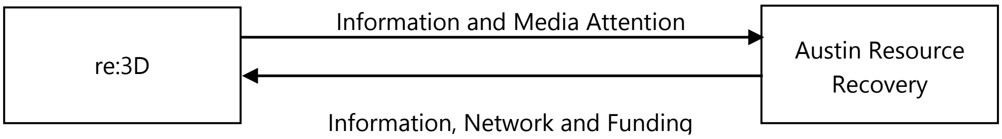
Direct: Home goods and art pieces

Urgency score	Dependence score

Reciprocal: Infrastructures and Funding

Urgency score	Dependence score

Flow 4:



Direct: Information and Media Attention

Urgency score	Dependence score

Reciprocal: Information, Network and Funding

Urgency score	Dependence score

THE END.

THANKS FOR YOUR COLLABORATION.

Questionnaire B.3

Austin [Re] Verse Pitch participation

This questionnaire intends to explore the process of developing an industrial symbiosis network in the additive manufacturing context.

Industrial symbiosis is a cooperative model that aims to improve resources to gain more significant mutual benefits rather than the benefits that could be obtained individually. Different entities interact with each other through the exchange of resources in a value network – the industrial symbiosis network. However, the concept of industrial symbiosis is marginally exploited in the context of additive manufacturing; this emerging technology has disruptive potential regarding using different materials as secondary raw materials.

Your contribution is extremely important for the development of this study. Please accept to collaborate with this investigation through the filling of this questionnaire.

I – Identification of the value flows exchanged within the network

The researchers mapped the flows exchanged within the network (fig.1) between the stakeholders. **Please validate and complete the information below considering the flows where the Austin [Re] Verse Pitch Competition entity takes part of (namely flows 3 and 4), and in case of changing, please mark your changes.**

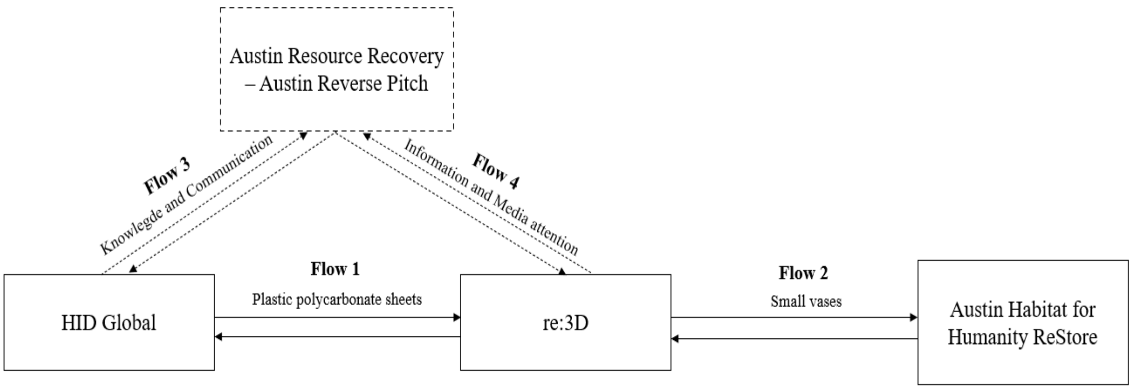


Figure 1 – Industrial Symbiosis Network inherent to the project "*Trash to Treasure*"

Flow 3:

Direct: Knowledge and Communication

Reciprocal: Information

Please validate this flow by choosing the right option from the box.

If choosing "incorrect", define the resource(s) exchange(s). ___________

Flow 4:

Direct: Information and Media Attention

Reciprocal: Information and Funding

Please validate this flow by choosing the right option from the box.

If choosing "incorrect", define the resource(s) exchange(s). ___________

II - Quantifying the value flows

After identifying the value flows, there is a need to quantify them. Therefore, the researchers consider the attributes "urgency" and "dependence" to identify the relative importance of value flows in the symbiosis network, namely:

- **Urgency attribute** - defined by the urgency for the receiving stakeholder to get a certain resource (scores given in table 1).

Table 1 – Urgency score and levels according to Feng et al. (2013, p.160).

Urgency score	Urgency levels
0.11	It can be fulfilled after four years from now
0.22	It should be fulfilled between the third and fourth year from now
0.33	It should be fulfilled between the second and third year from now
0.66	It must be fulfilled next year

0.98	It must be fulfilled this year

- **Dependence attribute** - this score aims to measure the dependence of a specific stakeholder to supply a particular resource. This score reveals the number of alternatives of variety in providing a resource. The higher the reliance on a stakeholders' provisions of a resource (e.g., if there are just one source and no available alternatives for a specific resource), a higher score of dependence is awarded (Ferreira et al., 2019).

Table 2 – Dependency score and levels according to Feng et al. (2013, p. 161).

Dependence score	Dependence levels
0.11	Not important – I do not need this source to fulfil this need
0.33	Somewhat important – It is acceptable that this source fulfils this need
0.55	Important – It is preferable that this source fulfils this need
0.78	Very important – It is strongly desirable that this source fulfils this need
0.98	Extremely important – It is indispensable that this source fulfils this need

For the flows that follow, please select the most suitable option for each criterion.

A) Flow 3: for the direct flow, where *"Knowledge and Communication"* are the resources exchange, please select one option for each attribute.

- Urgency score – "When does The Austin [Re]Verse Pitch Competition needs this resource fulfilled?"

- Dependence score – "How important is for The Austin [Re]Verse Pitch Competition to have HID Global as a supplier of this resource?"

Urgency score	Dependence score

B) Flow 4: For the direct flow, where *"Information and Media Attention"* are the resources exchange, please select one option for each attribute.

- Urgency score – "When does The Austin [Re]Verse Pitch Competition needs this resource fulfilled?"

- Dependence score – "How important is for The Austin [Re]Verse Pitch Competition to have re:3D as a supplier of this resource?"

Urgency score	Dependence score

III - Respondent's profile

1. Function/job: _

2. Professional experience (years):

THE END.

THANKS FOR YOUR COLLABORATION.

Questionnaire B.4

HID Global participation

This questionnaire intends to explore the process of developing an industrial symbiosis network in the additive manufacturing context.

Industrial symbiosis is a cooperative model that aims to improve resources to gain more significant mutual benefits rather than the benefits that could be obtained individually. Different entities interact with each other through the exchange of resources in a value network – the industrial symbiosis network. However, the concept of industrial symbiosis is marginally exploited in the context of additive manufacturing; this emerging technology has disruptive potential regarding using different materials as secondary raw materials.

Your contribution is extremely important for the development of this study. Please accept to collaborate with this investigation through the filling of this questionnaire.

I – Identification of the value flows exchanged within the network

The researchers mapped the flows exchanged within the network (fig.1) between the stakeholders. **Please validate and complete the information below considering the flows where the HID Global entity takes part in (namely flows 1 and 3), and in case of changing, please mark your changes.**

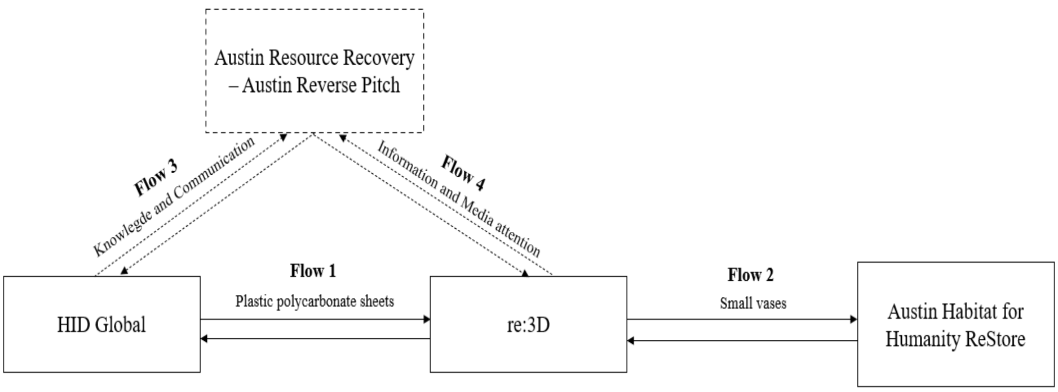


Figure 1 – Industrial Symbiosis Network inherent to the project "*Trash to Treasure*"

Please fill the blink for the direct flow with the resource(s) exchange(s) between HID Global to the Austin [Re]Verse Pitch Competition (flows 1 and 3).

Flow 1:

Direct: Material – plastic polycarbonate sheets

Reciprocal: Information and Knowledge

Please validate this flow by choosing the right option from the box.

If choosing "incorrect", define the resource(s) exchange(s). ____________________

Flow 3:

Direct: __________________________________

Reciprocal: Information

Please validate this flow by choosing the right option from the box.

If choosing "incorrect", define the resource(s) exchange(s). ____________________

II - Quantifying the value flows

After identifying the value flows, there is a need to quantify them. Therefore, the researchers consider the attributes "urgency" and "dependence" to identify the relative importance of value flows in the symbiosis network, namely:

- **Urgency attribute** - defined by the urgency for the receiving stakeholder to get a certain resource (scores given in table 1).

Table 1 – Urgency score and levels according to Feng et al. (2013, p.160).

Urgency score	Urgency levels
0.11	It can be fulfilled after four years from now
0.22	It should be fulfilled between the third and fourth year from now
0.33	It should be fulfilled between the second and third year from now
0.66	It must be fulfilled next year
0.98	It must be fulfilled this year

- **Dependence attribute** - this score aims to measure the dependence of a specific stakeholder to supply a particular resource. This score reveals the number of alternatives of variety in providing a resource. The higher the reliance on a stakeholders' resource provisions (e.g., if there are just one source and no available alternatives for a specific resource), the higher the dependence score is awarded (Ferreira et al., 2019).

Table 2 – Dependency score and levels according to Feng et al. (2013, p. 161).

Dependence score	Dependence levels
0.11	Not important – I do not need this source to fulfil this need
0.33	Somewhat important – It is acceptable that this source fulfils this need
0.55	Important – It is preferable that this source fulfils this need
0.78	Very important – It is strongly desirable that this source fulfils this need
0.98	Extremely important – It is indispensable that this source fulfils this need

For the flows that follow, please select the most suitable option for each criterion.

A) Flow 1: For the reciprocal flow, where *"Information and Knowledge"* are the resources exchange, **please select one option for each attribute.**

- Urgency score – "When does HID Global need this resource fulfilled?"

- Dependence score – "How important is for HID to have re:3D as a supplier of this resource?"

Urgency score	Dependence score

B) Flow 3: For the reciprocal flow, where *"Information"* is the resource exchange, **please select one option for each attribute.**

- Urgency score – "When does HID Global need this resource fulfilled?"

- Dependence score – "How important is for HID to have The Austin [Re]verse Pitch Competition as a supplier of this resource?"

Urgency score	Dependence score

III - Respondent's profile

1. Function/job: _

2. Professional experience (years):

THE END.

THANKS FOR YOUR COLLABORATION.

APPENDIX C

Combination rule for calculating the aggregated value scores, considering the "urgency" and "dependence" criteria from Feng (2013) (table 1).

Table 1 - Combined punctuation for the "urgency" and "dependence" criteria. Retrieved from Feng (2013).

Dependence score	**0.98**	0.11	0.22	0.32	0.65	0.96
	0.78	0.09	0.17	0.26	0.51	0.76
	0.55	0.06	0.12	0.18	0.36	0.54
	0.33	0.04	0.07	0.11	0.22	0.32
	0.11	0.01	0.02	0.04	0.07	0.11
		0.11	**0.22**	**0.33**	**0.66**	**0.98**
		Urgency score				

The scores attributed to each value flow from the participant stakeholders within the additive symbiotic network under study are represented in table 2 and the respective aggregated score. An explanation is provided to understand how to choose the right aggregated value from the aggregated scores presented in Table 1.

Table 1 – Scores attributed to the "urgency" and "dependence" criteria and resulting aggregated value for the flows within the additive symbiotic network from case study A

Value flows		Urgency score	Dependence score	Aggregated value
Flow 1	Direct	0.98	0.78	0.76
	Reciprocal	0.98	0.55	0.54
Flow 2	Direct	0.66	0.78	0.51
	Reciprocal	0.98	0.78	0.76
Flow 3	Direct	0.98	0.78	0.76
	Reciprocal	0.98	0.78	0.76
Flow 4	Direct	0.98	0.55	0.54
	Reciprocal	0.98	0.98	0.96
Explanation for the aggregated value of flow 1 – direct: Considering that the stakeholder involved in the exchange attributed an urgency score of 0.98 and a dependence score of 0.78, the aggregated value that results from intersecting the column of the urgency score of 0.98 and the line of the dependence score of 0.78 in the table from the combined punctuation of both criteria, results in a value of 0.76.				

APPENDIX D

Questionnaire D.1

Industrial symbiosis networks within the additive manufacturing industry

This questionnaire intends to explore the process of developing an industrial symbiosis network in the additive manufacturing context.

Industrial symbiosis is a cooperative model that aims to improve resources to gain more significant mutual benefits rather than the benefits that could be obtained individually. Different entities interact with each other through the exchange of resources in a value network – the industrial symbiosis network. However, the concept of industrial symbiosis is marginally exploited in the context of additive manufacturing; this emerging technology has disruptive potential regarding using different materials as secondary raw materials.

Your contribution is extremely important for the development of this study. Please accept to collaborate with this investigation through the filling of this questionnaire.

Please answer the following questions:

1 – WASTE'S IDENTIFICATION AND CHARACTERISTICS

1.1 Waste's identification (name) and its main characteristics (shape, dimensions, composition/materials):

1.2 Waste's origin (where it came from or in what process(es) are produced the by-product):

1.3 Identification of the final product that will be produced incorporating the waste:

1.4 Identification of the process(es) needed for waste recycling (for example: sorting, cleaning, melting, extrusion, among others.):

1.5 Who or which entity is responsible for the recycling process (including all the necessary waste treatment):

2 – STAKEHOLDERS' AND FLOWS' IDENTIFICATION

*By stakeholder, we consider the group of actors who participate, influence or have an interest in the symbiosis relationship

2.1 Identification of the stakeholders involved in the process (examples are companies, universities, labs, non-governmental organizations, etc.):

2.2 Identification of the exchanges that occur between the stakeholders (exchanges include: information, material, infrastructures, etc.):

2.3 Identification of to whom is sell the final product (produced using the waste):

2.4 Identification of any needs for waste transportation (please specify: what material needs transportation, whose responsibility it is and how are the materials transported):

3 - COMPANY'S PROFILE

3.1 Company/organization name (optional):

3.2 Business volume in 2019 (if applicable):

3.3 Number of employees (please choose the option that suits the best):

<10	10-49	50-250	>250

3.4 Company's age (please choose the option that suits the best):

<2 years	2-5 years	5-10 years	>10 years

3.5 Identification of the type of 3D printing equipment that the company has:

3.6 Year when the additive technology was introduced in the company (if applicable):

3.7 Identification of the company's main products:

3.8 Identification of the main sector of economic activity of the company's clients:

4 - RESPONDENT'S PROFILE

4.1 Function/job:

4.2 Professional experience (years):

THE END.

THANKS FOR YOUR COLLABORATION.

Questionnaire D.2

Additive symbiotic network – mapping and quantifying the value flows

This questionnaire intends to explore the process of developing an industrial symbiosis network in the additive manufacturing context. Your contribution is extremely important for the development of this study. Please accept to collaborate with this investigation through the filling of this questionnaire.

I - Identification of the value flows exchanged within the network

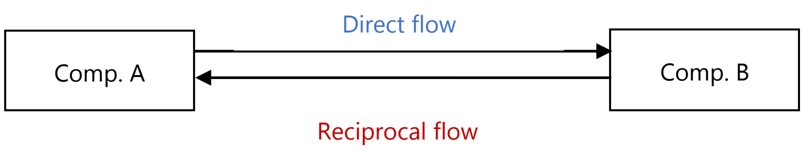
At this stage of the research, there is a need to identify and quantify the value flows that are exchanged within the symbiotic network and to do it, there are some elements that need to be considered, namely:

Table 1 - Description of the main elements to be considered

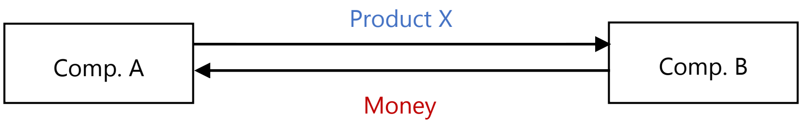
Value	A beneficial action for the participant who practises it. Stakeholders can exchange value directly or indirectly, through resource sharing or exchanges of information and knowledge.
Resource	Essentially everything that a participant in the value network considers as valuable.
Value Flow	It represents a value delivery between two stakeholders, for example, a normal transaction of buying a product has two value flows that can define it: one for the product and other for the money.

There are two types of flows:

- Direct – flow exchange from company A to company B and
- Reciprocal flow – from company B to company A.



For example, if company A produces a product that sells to company B, in exchange for money, there is a direct value flow from company A to company B that corresponds to the product that is sold. The reciprocal flow corresponds to the money that company B gives to company A in exchange for the product.



For this specific case study, and after the first questionnaire, the researchers mapped the network with the flows exchanged (fig.1) between the stakeholders and for each value flow, the direct and reciprocal flows were identified as follows (table 2). **Please validate the information below and mark your changes in case of change.**

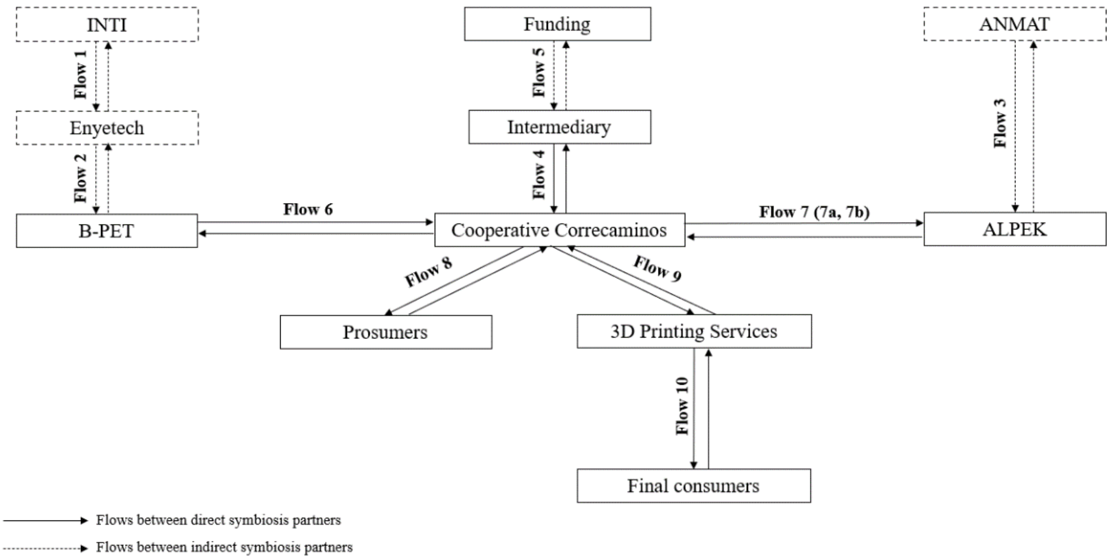


Figure 1 - Additive symbiotic network inherent to the case study

Table 2 – Direct and reciprocal flows exchanged within the additive symbiotic network

Flow nr.	Direct flow	Reciprocal flow
1	Research & development	Money
2	Funding	Money
3	Approval to produce food-grade pellets	Money
4	Funding network	Share of funding
5	Project presentation	Funding
6	3D technology and consulting services	Money
7a.	Bales of PET bottles	Money
7b.	Money	PCR PET pellets or flakes
8	3D filament	Money
9	3D filament	Money
10	Customized products & services	Money

II - Quantifying the value flows

After identifying the value flows, there is a need to quantify them. Therefore, the researchers consider the attributes "urgency" and "dependence" to identify the relative importance of value flows in the symbiosis network, namely:

- **Urgency attribute** - defined by the urgency for the receiving stakeholder to get a certain resource Scores are given in table 1.

Table 1 – Urgency score and levels according to Feng et al. (2013, p.160).

Urgency score	Urgency levels
0.11	It can be fulfilled after four years from now
0.22	It should be fulfilled between the third and fourth year from now
0.33	It should be fulfilled between the second and third year from now
0.66	It must be fulfilled next year
0.98	It must be fulfilled this year

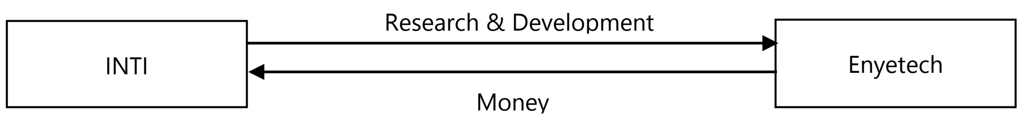
- **Dependence attribute** - this score aims to measure the dependence of a specific stakeholder to supply a particular resource. This score reveals the number of alternatives of variety in providing a resource. The higher the reliance on a stakeholders' resource provisions (e.g., if there are just one source and no available alternatives for a specific resource), the higher the dependence score is awarded (Ferreira et al., 2019). Scores are given in table 2.

Table 2 – Dependency score and levels according to Feng et al. (2013, p. 161).

Dependence score	Dependence levels
0.11	Not important – I do not need this source to fulfil this need
0.33	Somewhat important – It is acceptable that this source fulfils this need
0.55	Important – It is preferable that this source fulfils this need
0.78	Very important – It is strongly desirable that this source fulfils this need
0.98	Extremely important – It is indispensable that this source fulfils this need

For each of the value flows please choose the suitable punctuation for each of the criteria.

Flow 1:



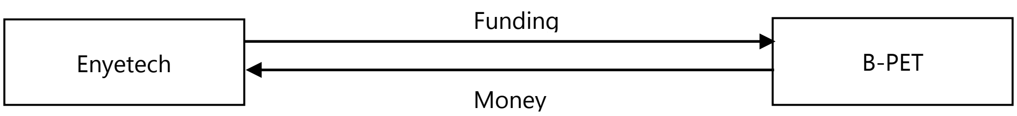
Direct: Research & Development

Urgency score	Dependence score

Reciprocal: Money

Urgency score	Dependence score

Flow 2:



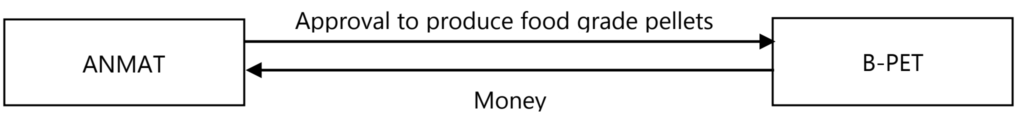
Direct: Funding

Urgency score	Dependence score

Reciprocal: Money

Urgency score	Dependence score

Flow 3:



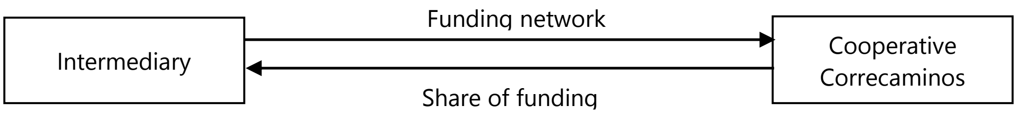
Direct: Approval to produce food-grade pellets

Urgency score	Dependence score

Reciprocal: Money

Urgency score	Dependence score

Flow 4:



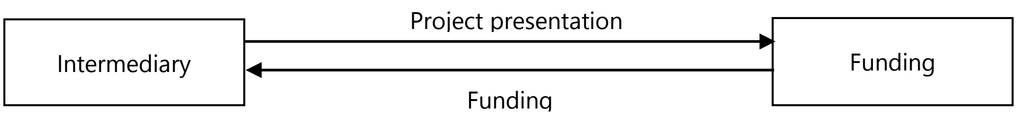
Direct: Funding network

Urgency score	Dependence score

Reciprocal: Share of funding

Urgency score	Dependence score

Flow 5:



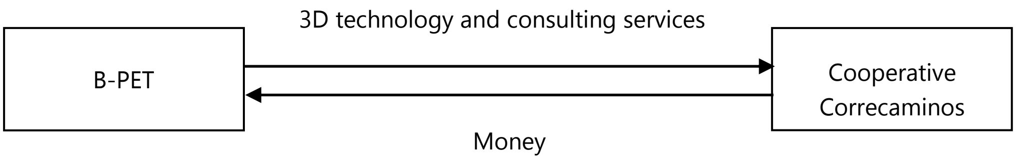
Direct: Project presentation

Urgency score	Dependence score

Reciprocal: Funding

Urgency score	Dependence score

Flow 6:



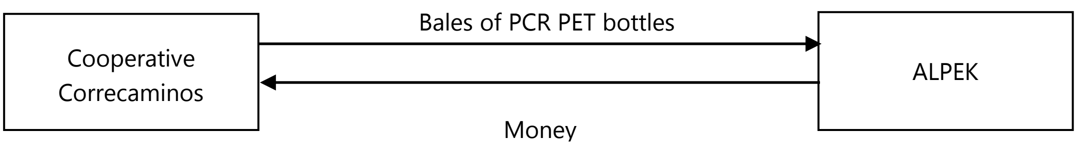
Direct: 3D Printing technology and consulting services

Urgency score	Dependence score

Reciprocal: Money

Urgency score	Dependence score

Flow 7a:



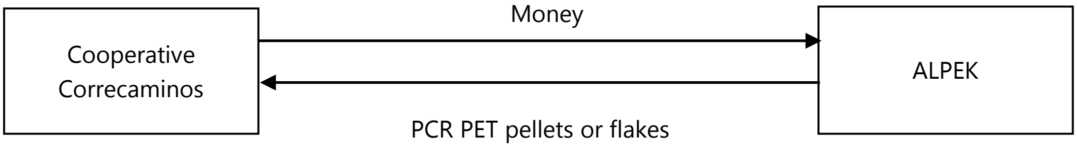
Direct: Bales of PCR PET bottles

Urgency score	Dependence score

Reciprocal: Money

Urgency score	Dependence score

Flow 7b:



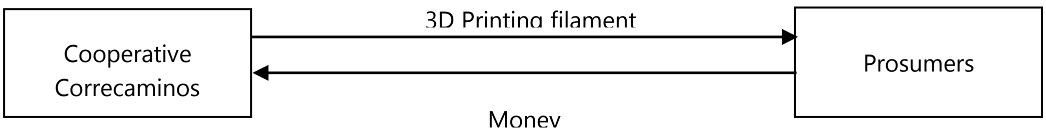
Direct: Money

Urgency score	Dependence score

Reciprocal: PCR PET pellets or flakes

Urgency score	Dependence score

Flow 8:



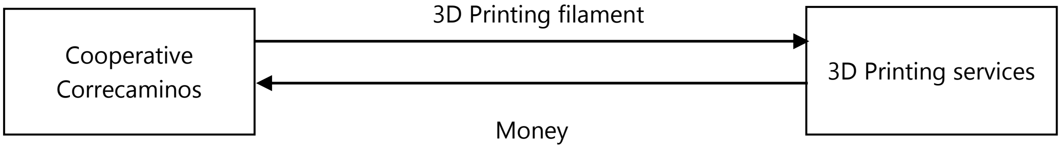
Direct: 3D Printing filament

Urgency score	Dependence score

Reciprocal: Money

Urgency score	Dependence score

Flow 9:



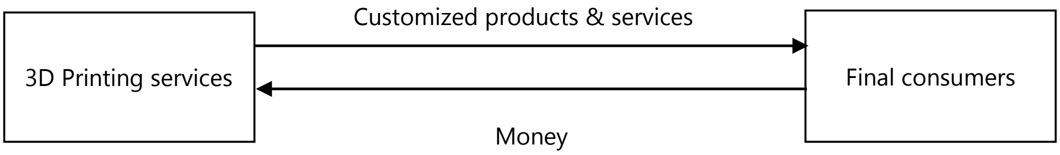
Direct: 3D Printing filament

Urgency score	Dependence score

Reciprocal: Money

Urgency score	Dependence score

Flow 10:



Direct: Customized products & services

Urgency score	Dependence score

Reciprocal: Money

Urgency score	Dependence score

THE END.

THANKS FOR YOUR COLLABORATION.

Questionnaire D.3

Blockchain-driven additive symbiotic network

This questionnaire intends to understand the potential implications of the relationships between the stakeholders of an additive symbiotic network with the adoption of blockchain technology. Your contribution is extremely important for the development of this study. Please accept to collaborate with this investigation through the filling of this questionnaire.

I - Identification of the value flows exchanged within the network

In this research phase, a potential scenario that uses blockchain technology in the symbiotic network was drawn. This scenario considers that with the application of the blockchain technology, the inherent supply chain of the symbiotic network may implicate changes in different areas, namely (Cole et al., 2019): i) in improving and automating contracts, ii) reducing the need to develop trustworthy supply chain relationships, iii) reducing the need for intermediaries and iv) reducing the transactions costs through automation. Considering these implications, please validate the new network's configuration (fig. 1) that was developed and validate the respective exchanged value flows (table 1). **Please validate the information below and mark your changes in case of change.**

A – New configuration of the additive symbiotic network – mapping

These changes include the exclusion of some stakeholders (namely, the Intermediary) and may potentially have implications with other stakeholders and other value flows within the network. Please validate the new map of the network from figure 1.

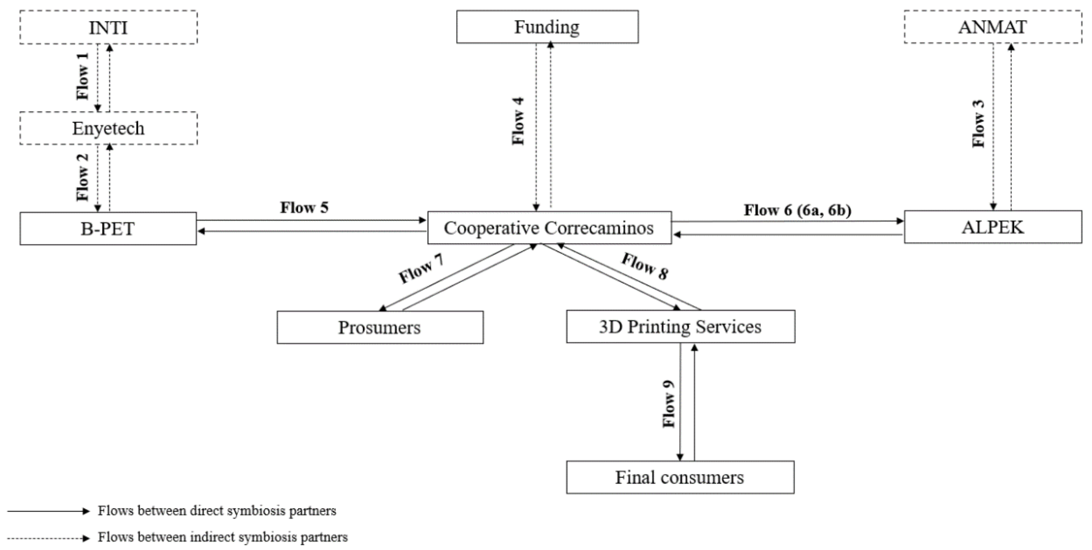


Figure 1 - Additive symbiotic network Mapping in a possible scenario after the application of the blockchain

B – Identifying the value flows for the new configuration

Considering the implications of adopting the blockchain technology in the supply chain of this additive symbiotic network, please validate the value flows exchanged for the scenario that was developed (Table 1). In case of change, please mark your changes.

Table 1 – Direct and reciprocal flows exchanged within the additive symbiotic network in the scenario after the application of the blockchain technology

Flow nr.	Direct flow	Reciprocal flow
1	Research & development	Money
2	Funding	Money
3	Approval to produce food-grade pellets	Money
4	Funding network	Money
5	3D technology and consulting services	Money
6a.	Bales of PET bottles	Money
6b.	Money	PCR PET pellets or flakes
7	3D filament	Money
8	3D filament	Money
9	Customized products & services	Money

II - Quantifying the value flows

After identifying the changes that may occur in the stakeholders and the respective value flows with the adoption of the blockchain technology, there is a need to understand if, with the adoption of the technology, the strength of the relationships between the stakeholders may also suffer additional changes. Thus, there is a need to quantify the value flows. For each value flow, please consider the attributes "urgency" and "dependence", as below (tables 2 and 3).

Table 2 – Urgency score and levels according to Feng et al. (2013, p.160).

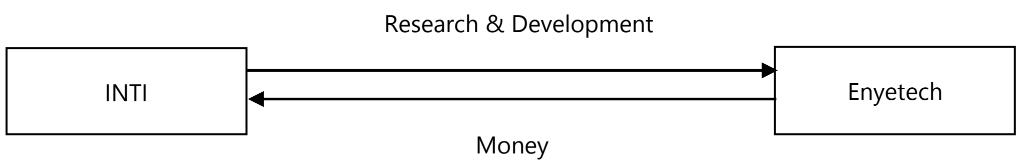
Urgency score	Urgency levels
0.11	It can be fulfilled after four years from now
0.22	It should be fulfilled between the third and fourth year from now
0.33	It should be fulfilled between the second and third year from now
0.66	It must be fulfilled next year
0.98	It must be fulfilled this year

Table 3 – Dependency score and levels according to Feng et al. (2013, p. 161).

Dependence score	Dependence levels
0.11	Not important – I do not need this source to fulfil this need
0.33	Somewhat important – It is acceptable that this source fulfils this need
0.55	Important – It is preferable that this source fulfils this need
0.78	Very important – It is strongly desirable that this source fulfils this need
0.98	Extremely important – It is indispensable that this source fulfils this need

For each value flow, please choose the suitable punctuation for each criteria, taking into account the implications of using the blockchain technology within the supply chain of the additive symbiotic network.

Flow 1:



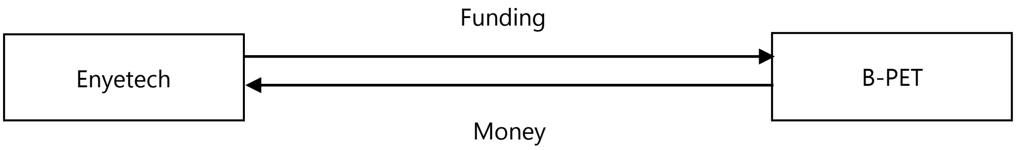
Direct: Research & Development

Urgency score	Dependence score

Reciprocal: Money

Urgency score	Dependence score

Flow 2:



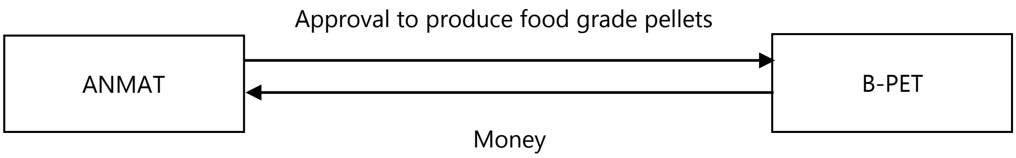
Direct: Funding

Urgency score	Dependence score

Reciprocal: Money

Urgency score	Dependence score

Flow 3:



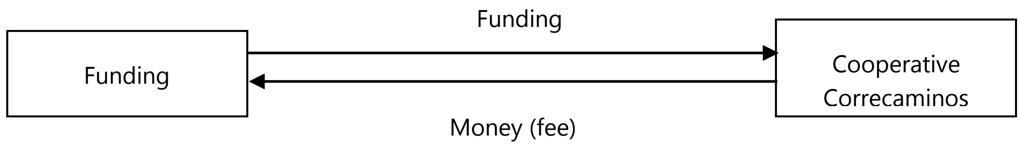
Direct: Approval to produce food-grade pellets

Urgency score	Dependence score

Reciprocal: Money

Urgency score	Dependence score

Flow 4:



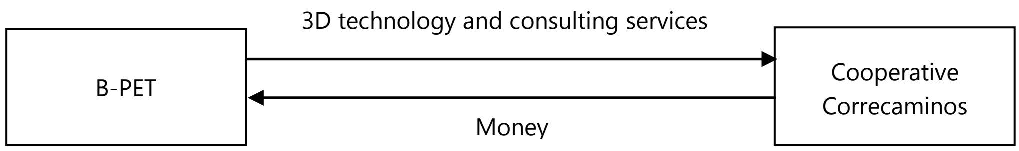
Direct: Funding

Urgency score	Dependence score

Reciprocal: Money (fee)

Urgency score	Dependence score

Flow 5:



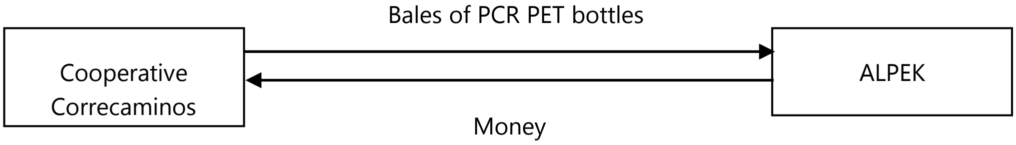
Direct: 3D Printing technology and consulting services

Urgency score	Dependence score

Reciprocal: Money

Urgency score	Dependence score

Flow 6a:



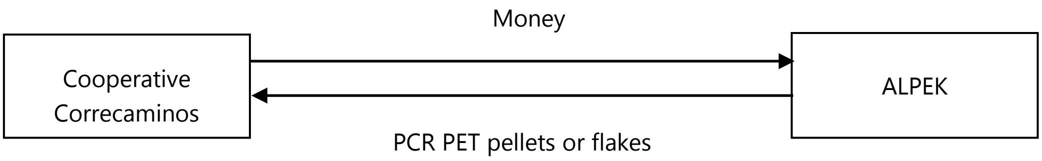
Direct: Bales of PCR PET bottles

Urgency score	Dependence score

Reciprocal: Money

Urgency score	Dependence score

Flow 6b:



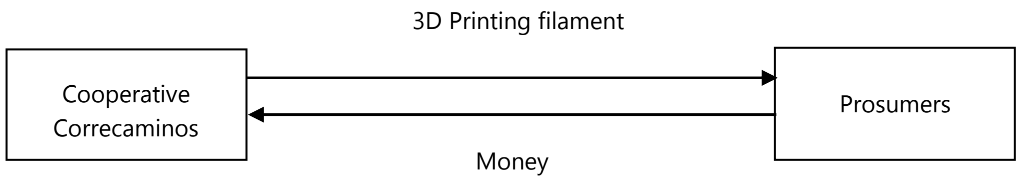
Direct: Money

Urgency score	Dependence score

Reciprocal: PCR PET pellets or flakes

Urgency score	Dependence score

Flow 7:



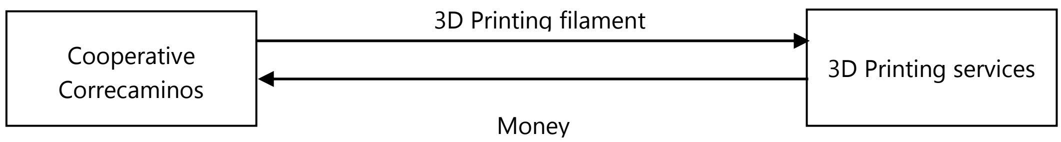
Direct: 3D Printing filament

Urgency score	Dependence score

Reciprocal: Money

Urgency score	Dependence score

Flow 8:



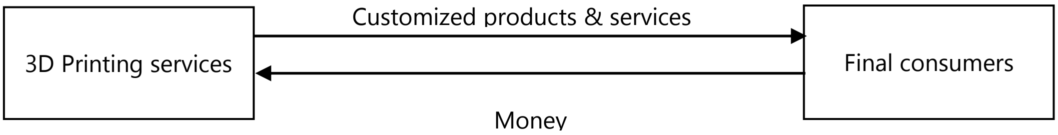
Direct: 3D Printing filament

Urgency score	Dependence score

Reciprocal: Money

Urgency score	Dependence score

Flow 9:



Direct: Customized products & services

Urgency score	Dependence score

Reciprocal: Money

Urgency score	Dependence score

THE END.

THANKS FOR YOUR COLLABORATION.

APPENDIX E

The scores attributed to each value flow from the participant stakeholders within the additive symbiotic network under study before and after adopting blockchain technology are represented in tables 1 and table 2 and the respective aggregated score, respectively.

Table 1 – Scores attributed to the "urgency" and "dependence" criteria and resulting aggregated value for the flows within the additive symbiotic network from case study B (before adopting the blockchain technology)

Value flows		Urgency score	Dependence score	Aggregated value
Flow 1	Direct	0.66	0.78	0.51
	Reciprocal	0.98	0.11	0.11
Flow 2	Direct	0.98	0.98	0.96
	Reciprocal	0.11	0.11	0.01
Flow 3	Direct	0.98	0.78	0.76
	Reciprocal	0.66	0.33	0.22
Flow 4	Direct	0.33	0.55	0.18
	Reciprocal	0.98	0.55	0.54
Flow 5	Direct	0.98	0.33	0.32
	Reciprocal	0.98	0.78	0.76
Flow 6	Direct	0.98	0.98	0.96
	Reciprocal	0.66	0.98	0.65
Flow 7a	Direct	0.98	0.98	0.96
	Reciprocal	0.98	0.98	0.96
Flow 7b	Direct	0.66	0.33	0.22
	Reciprocal	0.98	0.33	0.32
Flow 8	Direct	0.98	0.33	0.32
	Reciprocal	0.98	0.55	0.54
Flow 9	Direct	0.98	0.11	0.11
	Reciprocal	0.98	0.98	0.96
Flow 10	Direct	0.98	0.78	0.76
	Reciprocal	0.98	0.98	0.96

Table 2 – Scores attributed to the "urgency" and "dependence" criteria and resulting aggregated value for the flows within the additive symbiotic network from case study B (after adopting the blockchain technology)

Value flows		Urgency score	Dependence score	Aggregated value
Flow 1	Direct	0.66	0.78	0.51
	Reciprocal	0.98	0.11	0.11
Flow 2	Direct	0.98	0.98	0.96
	Reciprocal	0.11	0.11	0.01
Flow 3	Direct	0.98	0.78	0.76
	Reciprocal	0.66	0.33	0.22
Flow 4	Direct	0.98	0.98	0.96
	Reciprocal	0.33	0.55	0.18
Flow 5	Direct	0.98	0.98	0.96
	Reciprocal	0.66	0.98	0.65
Flow 6a	Direct	0.98	0.98	0.96
	Reciprocal	0.98	0.98	0.96
Flow 6b	Direct	0.66	0.33	0.22
	Reciprocal	0.98	0.33	0.32
Flow 7	Direct	0.98	0.33	0.32
	Reciprocal	0.98	0.55	0.54
Flow 8	Direct	0.98	0.11	0.11
	Reciprocal	0.98	0.98	0.96
Flow 9	Direct	0.98	0.78	0.76
	Reciprocal	0.98	0.98	0.96

2022

Inês Ferreira

WASTE TO 3D PRINTING: THE DEVELOPMENT OF ADDITIVE SYMBIOTIC NETWORKS

WASTE TO 3D PRINTING: THE DEVELOPMENT OF ADDITIVE SYMBIOTIC NETWORKS

2022